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Episodic memory retrieval functionally relies on very rapid reactivation of sensory information

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Abstract

26 Episodic memory retrieval is assumed to rely on the rapid reactivation of sensory information that was present during encoding - a process termed 'ecphory'. We investigated the functional 27 relevance of this scarcely understood process in two experiments in human participants. We 28 29 presented stimuli to the left or right of fixation at encoding, followed by an episodic memory test with centrally presented retrieval cues. This allowed us to track the reactivation of lateralized 30 sensory memory traces during retrieval. Successful episodic retrieval led to a very early (~100-31 200 ms) reactivation of lateralized alpha/beta (10-25 Hz) electroencephalographic (EEG) power 32 decreases in the visual cortex contralateral to the visual field at encoding. Applying rhythmic 33 transcranial magnetic stimulation (rTMS) to interfere with early retrieval processing in the visual 34 35 cortex led to decreased episodic memory performance specifically for items encoded in the visual field contralateral to the site of stimulation. These results demonstrate for the first time that 36 37 episodic memory functionally relies on very rapid reactivation of sensory information.

Significance Statement

40 Remembering personal experiences requires a 'mental time travel' to revisit sensory information perceived in the past. This process is typically described as a controlled, relatively slow process. 41 However, by using electroencephalography to measure neural activity with a high time 42 43 resolution, we show that such episodic retrieval entails a very rapid reactivation of sensory brain areas. Employing transcranial magnetic stimulation to alter brain function during retrieval 44 revealed that this early sensory reactivation is causally relevant for conscious remembering. 45 These results give first neural evidence for a functional, preconscious component of episodic 46 remembering. This provides new insight into the nature of human memory and may help in the 47 understanding of psychiatric conditions that involve the automatic intrusion of unwanted 48 memories. 49 50

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Introduction

54	Perceived information can reverberate with stored memory traces (Tulving et al., 1983). This fast
55	and involuntary process is considered a decisive ingredient for the 'mental time travel' implied in
56	episodic memory retrieval, reinstating sensory features of study episodes and biasing subsequent
57	retrieval processes leading to the experience of recollection (Tulving, 1983; Tulving et al., 1983).
58	This fundamental memory mechanism, termed 'ecphory', has long been described
59	phenomenologically and studied behaviorally (Semon, 1911; Tulving, 1976, 1982).
60	Neurophysiological evidence for such fast reinstatement processes has not emerged until recently
61	(Waldhauser et al., 2012; Wimber et al., 2012; Jafarpour et al., 2014). Using electrophysiological
62	methods, these recent studies show that a reactivation of sensory memory traces can occur very
63	rapidly, within 500 ms after onset of a retrieval cue. However, whether this early reactivation
64	process functionally drives episodic memory retrieval, as assumed in the theoretical idea of
65	ecphory, remains unclear. We employed a visual-half field paradigm to identify the oscillatory
66	signature of early reactivation (Experiment 1) and, moreover, to show that ecphoric reactivation
67	is functionally relevant for episodic memory retrieval (Experiment 2).
68	Retrieval from episodic memory leads to a reactivation of sensory memory traces in the
69	hemisphere contralateral to the visual field of initial presentation (Slotnick and Schacter, 2006;
70	Waldhauser et al., 2012). We made use of this principle in order to track the rapid reactivation of
71	individual memory representations, measuring and modulating brain oscillatory activity by means
72	of electroencephalography (EEG, Experiment 1) and rhythmic transcranial magnetic stimulation
73	(rTMS, Experiment 2). Participants were engaged in instructed or non-instructed encoding of
74	everyday objects presented either in the left or right visual field (LVF/ RVF; Fig. 1). In a
75	subsequent retrieval task, memory cues were presented at the center of the screen and participants
76	engaged in item recognition followed by a source memory task. Source memory was examined to

test for the ability to retrieve contextual details of the study episode, which is considered ahallmark of episodic memory (Tulving, 1983).

Previous studies were able to localize memory reactivation effects during retrieval to 79 lateralized visual cortical areas active during encoding (Gratton, 1998; Slotnick, 2004; Slotnick 80 and Schacter, 2006) and investigated the timing of lateral reactivation in terms of event-related 81 potential effects (Gratton, 1998; Slotnick and Schacter, 2010). However, it still remains unclear if 82 and how rapid visual cortical reactivation is causally relevant to explicit episodic memory 83 (Slotnick and Schacter, 2010; Thakral et al., 2013), leaving a fundamental question of memory 84 theory unanswered. In order to shed light on these questions we investigated brain oscillations as 85 86 a highly sensitive, physiologically relevant measure of cortical activity. Following recent ideas (Hanslmayr et al., 2012), a desynchronization of oscillatory power in the alpha/beta frequency 87 bands indicates an increase in the complexity of firing patterns, thereby allowing for higher 88 89 information coding capacity during memory encoding and retrieval. Thus, we expected a specific decrease of alpha/beta oscillations in the brain hemisphere contralateral to the visual field of 90 encoding as a marker of memory reactivation. In line with the theoretical notion of ecphory, this 91 92 alpha/beta power decrease was hypothesized to occur very rapidly, i.e. within 500ms (Tulving et al., 1983; Waldhauser et al., 2012; Jafarpour et al., 2014), before the occurrence of signatures of 93 recollection and controlled retrieval processes (Rugg and Curran, 2007). Applying rhythmic 94 transcranial magnetic stimulation (rTMS) at the neural sources, in the time range, and with a 95 frequency as identified in the first experiment was expected to counteract the rapid reactivation of 96 97 visual cortical areas and lead to disrupt source memory performance. This would give strong evidence for the functional relevance of ecphoric processes for episodic remembering. 98

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Materials and Methods

102 Materials and Procedure

Materials, behavioral task, trial timing, and basic procedure were identical for
Experiments 1 and 2 (see Fig. 1). The study was approved by the Ethical Review Board at the
University of Konstanz.

Stimulus material. Two hundred and forty everyday objects (Rossion and Pourtois, 2004)
were used in each experiment. Half of these items were presented during encoding, serving as old
items during retrieval. Objects subtended a visual angle of 5.6° x 4° and were presented to the left
or right visual field (LVF/RVF), 4° below and 6° lateral from central fixation. Items were
preselected into 8 sets, so that semantic categories of the depicted objects, frequency of
occurrence, vividness, visibility and orientation (portrait vs. landscape) were balanced across
conditions.

113 *Procedure.* The experiment was carried out in two blocks, pertaining to the two encoding conditions (instructed and non-instructed encoding). Each block comprised the encoding phase, a 114 distracter task and a final retrieval phase. In the non-instructed encoding condition, participants 115 were supposed to engage in judging the size of each object. In the intentional encoding condition, 116 subjects were simply instructed to intentionally encode each object the best they could for later 117 118 retrieval. During encoding, participants responded with the index and middle finger of the right hand whether an item was larger or smaller than a shoebox or whether the item was easy or 119 difficult to encode. Allocation of response buttons to index or middle finger was counterbalanced 120 121 across subjects. The encoding phase was followed by a three-minute distracter task to prevent selective rehearsal, consisting of counting backwards aloud from a three digit number in steps of 122 three. During the subsequent retrieval task, 60 encoded items were presented at the center of the 123 screen as old items together with the same amount of new items. Participants were instructed to 124

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first engage in an old/new recognition test and subsequently tested for source memory, indicating 125 126 whether an item was presented to the left or right visual field during encoding. Participants responded with the index and middle finger of the right hand whether an item was old or new and 127 if the item was endorsed as old, whether the item was initially presented to right or left of 128 129 fixation. Allocation of response buttons to index or middle finger was counterbalanced across 130 subjects in the old/new task, but the middle finger was always used to indicate source endorsement to the RVF and the index finger was used to indicate LVF presentation. Succession 131 of encoding conditions, old/new status of items and presentation of the old items to the left or 132 right visual field during encoding were counterbalanced across subjects. 133

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Presentation of items within encoding phases was randomized so that each VF condition was followed by an item from the same or opposite VF condition with equal probability and under the constraint that the same VF could occur twice in a row. During retrieval, the sequence of items encoded in the left and right VF was also randomized under the same constraint (no more than two items from the same VF condition in a row). Additionally, old items were randomly intermixed with new items so that no more than four old or new items could occur in a row.

Analysis of behavioral data. Behavioral data during the final memory test were analyzed 141 based on a) hits, i.e. the number of correctly identified old items and b) source hits, i.e. the 142 number of hits for which VF of presentation was correctly identified in addition to correct item 143 recognition. Number of hits and source hits were each divided by the number of all old items for 144 145 each subject. Arguably, dividing the number of source hits by number of hits would give a cleaner measure of pure source memory performance in addition to simple item recognition. 146 However, we assumed that source memory performance is already constrained by item memory 147 148 performance in our case, so that a 'new' response to an old item (i.e., miss) prevents a correct

source memory judgment, as only an 'old' response prompts a subsequent source memory task. 149 150 In addition, item recognition performance may already be biased by source memory demands so that only items are endorsed as hits if a correct source memory judgment can be made. As a 151 consequence of our calculation method, source hit rates may appear rather low. Note that chance 152 153 level for source hits is below 50 %, since the probability to endorse an item as being presented in the LVF or RVF already depends on the probability to endorse an item as old or new (see, e.g., 154 155 Cycowicz et al., 2001; Batchelder & Riefer, 1990, for detailed discussion). In addition to the different types of hits, we report c) false alarms, new items that were incorrectly classified as old. 156 For Experiment 2 we also investigated d) source false alarms, new items that were incorrectly 157 158 endorsed as old and for which a source memory judgment was given. This analysis was conducted to determine whether rTMS affects the tendency to misattribute a new item to the VF 159 contra- or ipsilateral of stimulation. Behavioral data were analyzed in uncorrected repeated 160 161 measures ANOVAs or uncorrected two-sided paired t-tests.

162

163 Experiment 1

164 *Participants.* Sixteen right-handed (Oldfield, 1971) subjects (11 female) with a mean age 165 of 24 years (range 21 - 37), normal or corrected-to-normal vision, and no history of neurological 166 of psychiatric disease participated in this study. Participants received course credit or a monetary 167 reward of 20 \in for participating in the experiment. Informed consent was acquired from each 168 participant prior to the experiment.

Data analysis. EEG was recorded using equidistant 128 Ag/AgCl scalp electrodes (DC 100 Hz, 512 Hz sampling rate) referenced to common average. A time-frequency representation
 of the EEG signal (1-30 Hz) was derived by means of Morlet wavelets (width 5). Since we had
 no hypotheses concerning the different encoding tasks and since no statistical differences

between encoding tasks were obtained (see Results and Table 1), EEG power was collapsed
across encoding tasks. To quantify event-related signal changes on sensor level, poststimulus
power change was calculated in relation to a pre-stimulus baseline period (-500 to 0 ms) for both,
encoding and retrieval phases. No significant electrode clusters emerged between conditions in
the baseline interval in a fieldtrip cluster statistic calculated at all electrodes for the frequency
ranges of interest during encoding and retrieval.

179 To identify time-windows and the frequency range of interest, EEG power during encoding was first compared between LVF and RVF conditions in a sliding-time-window 180 fieldtrip cluster statistic (Maris and Oostenveld, 2007). Here, we continuously applied cluster-181 182 statistics for time and frequency windows of 200 ms and 2 Hz in steps of 100 ms and 1 Hz to the data from 1 to 30 Hz and from 0 to 1500 ms (Staudigl and Hanslmayr, 2013). Following our 183 184 hypotheses, we directly compared posterior electrodes over the respective hemisphere 185 contralateral to the VF of presentation between LVF and RVF conditions. We did so by inverting EEG power values in the RVF condition for each time and frequency point at left-hemispheric 186 parieto-occipital sensors through multiplication with -1. Then, we compared the result in each 187 time-frequency window with the corresponding (non-inverted) power values at right-hemispheric 188 sensors for the LVF condition. Each cluster statistic then reveals whether there is a contralateral 189 power decrease, with the highest likelihood of significant effects if there is a strong contralateral 190 decrease in both, LVF and RVF conditions. In order to correct for multiple comparisons, the 191 resulting 630 p-values were adjusted following the false discovery rate procedure (Benjamini and 192 193 Hochberg, 1995; Benjamini and Yekutieli, 2001). The result of this analysis indicated electrode clusters yielding significant EEG power differences between LVF and RVF conditions over the 194 respective contralateral hemispheres in the alpha/ lower beta range (8-20 Hz), most prominent 195 196 between 200 and 700 ms after stimulus presentation (see Fig. 3A, top).

However, the sliding cluster analyses can only suggest the presence of a statistical 197 198 difference between VF conditions at the contralateral hemispheres, but it is not able to reliably show the actual topographical clusters that differ between VF conditions and to take into account 199 ipsi- and contralateral sensors. To this end, we subtracted non-inverted data in the RVF from the 200 201 LVF condition and calculated a fieldtrip cluster statistic in the time (200-700 ms) and frequency 202 (8-20 Hz) window suggested by the sliding analysis, allowing us to identify significant electrode 203 clusters in each hemisphere (Fig. 3A, center). The mean EEG power at these clusters interacted significantly between VF (LVF/RVF) and left and right brain hemispheres (LH/RH, see Fig. 3A, 204 bottom), as indicated by a 2-way ANOVA. 205

206 In order to investigate lateralized activity during retrieval, EEG power differences between contra- and ipsilateral electrode clusters identified during encoding were averaged over 207 LVF and RVF conditions and compared over time in a frequency range between 1 and 30 Hz. 208 209 Results were masked by the results of running Wilcoxon signed-rank test applied at each time (~50 ms) and frequency (~0.5 Hz) bin resulting from the Morlet wavelet time-frequency 210 transformation. Since our hypotheses were concerned with rapid contralateral decreases in 211 212 alpha/beta power, we focused on early (< 500 ms) interaction effects as indicators for exploric processes. Negative values in Figure 3B (top) indicate uncorrected significant (P < .05) 213 differences between contra- minus ipsilateral electrodes collapsed across both VF conditions. 214 Based on the results of this exploratory analysis, the interaction between VF (LVF/RVF) and left 215 and right brain hemispheres was tested in an uncorrected 2-way repeated-measures ANOVA 216 taking into account mean EEG power (10-25 Hz, 100-200 ms) at the LH/RH clusters identified 217 during encoding (see Fig. 3B, bottom, for mean power depending on condition and hemisphere 218 and Fig. 3B, center, for topographical distribution of mean EEG power). In order to shed light on 219 220 hemisphere-specificity of these effects (Fig. 4), additional two-sided *t*-tests were carried out in

the 100-200 ms time window, comparing LVF- RVF differences in the hemisphere-specific peak
frequencies at the LH and RH electrode clusters.

In order to test whether reinstatement strength reflecting in a contralateral alpha/beta 223 power decrease is linked to behavioral performance, we compared the amount of lateralization 224 225 between source hits and source misses in a two-sided *t*-test. Lateralization was defined as the 226 mean difference between the contra- minus ipsilateral electrode clusters in the 10-25 Hz frequency band from 100 to 200 ms. We expected lateralization to be more negative for source 227 hits than source misses. In a second step, we also investigated whether single trials could be 228 identified as source hits and source misses (i.e. hits that were incorrectly attributed to the VF 229 230 opposite to the VF of actual presentation) based on the amount of contra-minus ipsilateral lateralization at the electrode clusters in the 10-25 Hz frequency band by means of a contingency 231 table (see Table 2). In this approach, EEG signals were not baseline corrected in order to avoid 232 233 misclassification of trials due to potentially higher baseline noise in non-averaged single trials. Instead, a lateralization index was estimated for each trial by correcting for the total power at the 234 contra- and ipsilateral electrodes (lateralization index = contralateral – ipsilateral / contralateral + 235 236 ipsilateral; cf. Händel et al., 2011). A lateralization index < 0 signifies a trial as having a relative power decrease at contralateral electrodes. We hypothesized that such trials would be classified 237 as source hits with a frequency above chance, whereas trials with a lateralization index > 0 would 238 more often be classified as source misses. We tested this assumption by means of a χ^2 -test for all 239 trials from all participants (i.e. fixed effects analysis). In order to make the data more accessible, 240 241 we also report classification performance in percent ((correctly classified source hits + correctly classified source misses) / all items) * 100). In addition, we also tested whether the mean 242 differences between observed cell frequencies and expected cell frequencies in chi-square tests 243

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across all participants were significantly different from zero on the group level by means of aone-sample *t*-test (i.e. random effects analysis).

To identify sources of oscillatory activity, we employed the Dynamic Imaging of 246 Coherent Sources (DICS) beamforming approach after calculating the cross-spectral density 247 248 matrix. We used individual electrode positions as acquired with a sensor digitization tool (XensorTM, www.ant-neuro.com) and the FieldTrip standard MRI. DICS constructs adaptive 249 spatial filters to localize power for each grid point in the entire brain (Gross et al., 2001; Gross et 250 al., 2003). For each individual and the time periods of interest during encoding and retrieval, 251 filters were calculated using activity following the encoding stimulus and the recognition cue, 252 253 respectively, and baseline periods corresponding to the length of the poststimulus period of 254 interest (Dalal et al., 2008), including the trials from both, LVF and RVF conditions. For encoding data, a baseline period from -500 to 0 ms and poststimulus period from 200 to 700 ms 255 256 were chosen. For retrieval data, a baseline period of -100 to 0 ms and a poststimulus period of 257 100 to 200 ms were chosen. Cross-spectral density and source power was estimated using frequency analysis with Slepian multitapers as implemented in FieldTrip (Oostenveld et al., 258 2011) for the frequency range observed at sensor level, i.e. 8-20 Hz for encoding and 10-25 Hz 259 for retrieval. The resulting average source estimate for each condition in the time intervals of 260 261 interest was corrected for source activity in the baseline interval and subsequently statistically compared with the other condition and interpolated to the standard Montreal Neurological 262 Institute (MNI) brain. In a final step, we aimed at identifying the voxels that differentiated with 263 264 most sensitivity between conditions across both hemispheres. To this end, we statistically compared the RVF-LVF power difference in the right hemisphere with the corresponding effect 265 in the left hemisphere in a one-sided FieldTrip source cluster statistic. This was done again for 266 267 both, encoding and retrieval effects. The results were again interpolated to the standard Montreal

Neurological Institute (MNI) brain (see Fig. 5). The obtained maximum inter-hemispheric
difference between conditions during retrieval was determined at MNI coordinates ± 40, -78, 0.
Source localization results were visualized using the Caret software (http://brainvis.wustl.edu).

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272 Experiment 2

Participants. Twenty-four right-handed subjects (14 female) with a mean age of 23 years 273 274 (range 18 - 27) and normal or corrected-to-normal vision completed the experiment. In addition to a general assessment of history of neurological and psychiatric disease and medication, an 275 additional TMS screening was conducted prior to the experiment (Rossi et al., 2011). 276 277 Furthermore, a detailed explanation of the TMS method and its risks was provided for the subjects (Rossi et al., 2009). Informed consent was acquired from each participant prior to the 278 experiment. One participant was excluded before the start of the study due to unclear status of 279 280 inner ear damage and one further person aborted the experiment because of neck pain during phosphene stimulation. Participants received course credit or a monetary reward of 20 € for 281 participating in the experiment and an extra 10 € for taking part in structural MRI assessment. 282

Procedure. Behavioral task and procedure were almost identical to Experiment 1. 283 Stimulation conditions were applied in a within-subject fashion during the retrieval phase of both 284 blocks. This required pausing the procedure every 40 trials in order to relocate the coil between 285 the hemispheres and change the tilt of the coil according to TMS and sham conditions. Old, new, 286 LVF and RVF items were equally distributed between these segments of 40 trials. Four subjects 287 288 received only 36 trials per stimulation block due to experimental error, but counterbalancing and matching of condition and stimulus material was preserved. rTMS was applied to the right and 289 left hemisphere during each of the two retrieval phases. Sham was applied to only one 290 291 hemisphere during a particular retrieval block in order to keep the blocks at reasonable size and

length. Succession of rTMS and Sham conditions was counterbalanced across subjects so that
stimulation conditions and hemispheres were equally often followed and preceded by the other
conditions.

TMS was applied with a Magstim Rapid² Transcranial Magnetic Stimulator via a 295 Magstim figure-of-eight coil. At the beginning of an experimental session, phosphene threshold 296 (PT) was identified in each subject, using the modified binary search (MOBS) procedure (Tyrrell 297 and Owens, 1988; Anderson and Johnson, 2006; Romei et al., 2010). To this end, subjects were 298 blindfolded and single TMS pulses were applied with the coil centered midline 2 cm above the 299 inion. Participants had to indicate the presence or absence of a phosphene by answering "yes" or 300 "no". PT is defined as the percentage of maximum stimulator output above which subjects 301 302 consistently report seeing phosphenes. PT served as an individual marker of cortical excitability and was used to determine stimulator output during the experiment. RTMS was applied with 90% 303 304 PT output, which corresponded to a mean stimulator output of 61.3 % (SD = 7.44). If no reliable PT could be determined (n = 3), a fixed stimulator output of 60 % was used (Romei et al., 2010). 305 No participant reported perception of phosphenes during the experiment. 306

307 In order to deliver magnetic pulses with high anatomical precision rTMS was guided by a neuronavigation system, which co-registers the individual MRI with the position of the TMS coil 308 using a 3D tracking device (ANTVisor; www.ant-neuro.com). Individual high-resolution T1-309 weighted MRIs were acquired from a Siemens Skyra 3 T scanner (Flip Angle = 7° ; TR = 310 2500 ms; TE = 4.06 ms) or based on other structural MRI scans from various sources if already 311 existing for the participant. Maximum magnetic field strength was applied to the neural source of 312 alpha/beta oscillatory decreases in the lateral occipital cortex as identified during retrieval in 313 Experiment 1 (MNI coordinates: ± 40 , -78, 0). Four TMS pulses were applied with a duration of 314

57 ms between pulses, with application starting at 33.5 ms and lasting until 204.5 ms after cue 315 316 presentation, corresponding to a frequency of 17.5 Hz (see Fig. 6A). Sham was applied by tilting the TMS coil in an angle of approximately 60° away from the 317 scalp surface, but still touching the head. Thereby, participants still experienced clicking noise 318 319 and slight vibrating sensation at the scalp surface (Sauseng et al., 2009). 320 321 Results Episodic memory retrieval is accompanied by a rapid decrease of alpha/beta oscillatory 322 power 323 324 In Experiment 1 (see Fig. 1), high-density EEG was measured during encoding and retrieval to reveal the oscillatory signature of memory reactivation. In a first step, we aimed at 325 identifying encoding-related lateralized brain activity. On a behavioral level, no difference 326 327 between encoding tasks (instructed vs non-instructed) or visual field conditions (LVF vs RVF) were obtained, neither on item recognition nor on source memory performance (all t_{15} s < 1.361, 328 Ps > 0.05; see Table 1). In addition, there was no difference between blocks determined by 329 330 encoding conditions in terms of false alarm rates ($t_{15} = 1.156$, P = 0.266; instructed: M = 11.6 %, SD = 8.91 %; non-instructed: M = 14.1 %, SD = 8.65 %). This allowed us to collapse the EEG 331 data across encoding instructions to enhance signal-to-noise ratio and to directly compare VF 332 conditions on a neural level. We compared EEG activity between RVF and LVF conditions at the 333 respective left- or right-hemispheric posterior contralateral electrodes in a sliding cluster statistic 334 335 (see Method section, Fig. 2) to isolate the time and frequency windows most sensitive to the expected contralateral power decreases at encoding. This was achieved by inverting power values 336 for the RVF condition at the left-hemispheric electrodes and comparing them with power at right-337 hemispheric electrodes for the LVF condition. This analysis indicated maximum power 338

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differences at contralateral electrodes between the VF conditions from 200-700 ms in the 339 340 alpha/beta range (8-20 Hz, p_{adi} < 0.05, FDR corrected; Fig. 3A, top (Genovese et al., 2002)). While this result pinpointed the time-and frequency range of lateral differences between VF 341 conditions, the analysis could neither indicate if the effect is stronger on contra- than ipsilateral 342 343 electrodes, nor answer exactly which electrodes are most sensitive to hemisphere and VF-specific 344 effects. Thus, we subtracted power in the LVF condition from power in the RVF condition in the identified time-frequency range, such that positive values reflect a stronger alpha/beta power 345 decrease in the RVF condition whereas negative values reflect a power decrease in the LVF 346 condition (Fig 3A, center). We calculated a cluster statistic on all electrodes to identify the 347 348 clusters most sensitive to VF specific decreases (Maris and Oostenveld, 2007). In line with our hypothesis, this analysis revealed one left- and one right hemispheric electrode cluster (left: P =349 0.038; right: P = 0.006), each most sensitive to a power decrease in the contralateral VF (see Fig. 350 351 3A, center). This VF x Hemisphere interaction was supplemented by a 2-way repeated measures ANOVA taking into account mean power at the identified electrode clusters ($F_{1.15} = 62.039, P < 10^{-1}$ 352 0.001), suggesting a significant power decrease at contralateral electrodes differing from 353 354 ipsilateral activity for each VF condition (see Fig 3A, bottom). Finally, we conducted a beamformer source analysis of the 8-20 Hz alpha/beta oscillatory activity between 200 and 700 355 ms (Gross et al., 2001; Gross et al., 2003). To obtain the maximum inter-hemispheric difference 356 between conditions, we subtracted the interpolated RVF-LVF power difference at source level in 357 the right hemisphere from the effect in the left hemisphere and vice versa. The source analysis, 358 359 localizing the maximum difference between contra- and ipsilateral hemispheres, revealed neural generators of the EEG effect in the lateral (middle and inferior) occipital gyrus (LOC, BA 18/19; 360 Fig. 5). 361

In order to reveal the neural signature of memory reactivation, we carried out statistical 362 363 analyses on those electrode clusters showing significant lateralization differences between LVF and RVF at encoding. Following previous EEG studies of memory reactivation (Wimber et al., 364 2012; Jafarpour et al., 2014; Johnson et al., 2015), and in line with the theoretical notion of 365 ecphory (Tulving et al., 1983), we focused our analysis at retrieval on a time-range preceding the 366 typical timing of recollection effects, before 500 ms after presentation of the retrieval cue. As 367 indicated by a continuous Wilcoxon sign-rank test, a significant difference between ipsi- and 368 contralateral electrode clusters emerged very early, 100-200 ms after cue presentation (Ps < 0.05), 369 and in a similar frequency band as during encoding, between 10-25 Hz (see Fig. 3B, top). This 370 371 difference, again, was due to a power decrease at the electrode cluster contralateral to the VF of presentation during encoding, as indicated by a significant VF x hemisphere interaction ($F_{1,15}$ = 372 8.773, P = 0.01, see Figure 3B). This effect appeared to be different between hemispheres in 373 374 terms of peak frequencies. As shown in Figure 4A, differences between VF conditions were 375 clustered around 20 Hz in the RH cluster whereas the LH cluster displayed a more specific effect at around 10 Hz. Frequency-specificity of the two hemispheres was confirmed in a statistical 376 analysis, showing that only the LH cluster showed a significant VF difference at 10 Hz (t_{15} = 377 2.332, P = 0.034) and only the RH cluster showed a significant VF difference at 20 Hz (t_{15} = 378 2.616, P = 0.02; Fig. 4B). However, based on our previous studies, and following the idea that we 379 tap into similar oscillatory processes in the two hemispheres, we continued our analyses with data 380 integrated over the whole frequency range showing a mean contra- versus ipsilateral difference 381 382 (Waldhauser et al., 2012).

In order to check whether contra- versus ipsilateral differences in the 10-25 Hz frequency range are indeed due to a poststimulus decrease, and not due to a prestimulus shift of attention,

we repeated the same analysis taking into account the raw data from the baseline (-500 to 0 ms) interval. This analysis yielded no significant results ($F_{1,15}$ s < 3.554, Ps > 0.05).

According to theories on episodic memory, an ecphoric reactivation of trace information 387 is a prerequisite for the recollection of details of an episode. Thus, we expected it to be most 388 pronounced for source hits, for which the source of encoding could be correctly remembered. In 389 line with this idea, the contra- versus ipsilateral alpha/beta power decrease was significantly 390 greater for source hits (M = -7.13 % SD = 9.631), when compared to source misses ($t_{15} = 4.061$, 391 P = 0.001), the latter actually showing a relative power increase at contralateral electrodes (M =392 7.27 %, SD = 12.534). The lateralization effects for source hits and source misses were both 393 significantly different from zero (source hits: $t_{15} = -2.962$, P = 0.01; source misses: $t_{15} = 2.320$, P 394 = 0.035). These results suggest that the laterality of EEG power predicts to which VF an item is 395 attributed to, in a way that subjects tend to attribute an item to the VF that is contralateral to the 396 hemisphere displaying a power decrease. As shown in Table 2, this was also the case on a single-397 trial level. Source hit trials more often showed a negative lateralization index, i.e., a power 398 decrease at electrodes contralateral to the VF in which the item was actually presented during 399 400 encoding. Source miss trials more often showed a positive lateralization index, i.e., a power decrease over the ipsilateral hemisphere (see Table 2). A dependency of lateralization and 401 response was confirmed statistically in a fixed effects analysis ($\chi_1^2 = 4.731$, P = 0.03), showing 402 that 53 % of all items were classified correctly as source hits and source misses based on EEG 403 lateralization. This statistical dependency was also confirmed in a random effects analysis on 404 group level, with the mean difference between observed and expected cell values being 405 significantly greater than zero (M = 0.951, SD = 1.6374; $t_{15} = 2.25$, P = 0.04). Notably, 11 (out of 406 16) participants numerically showed this classification pattern (i.e. mean differences > 0) on the 407 408 single trial level. Lateralization and memory performance was independent when taking into

409 account the baseline interval from -500 to 0 ms on a single trial level ($\chi_1^2 = 1.8467, P = 0.174$). 410 Classification of source hits and source misses across all subjects based on EEG lateralization 411 was close to chance (49 %). This accorded with a random effects analysis when comparing 412 individual differences between expected and observed frequencies against zero (M = 0.647, SD =413 1.317; $Z = 1.448, t_{15} = 1.885, P = 0.079$).

Finally, we aimed at localizing the neural generators of alpha/beta power decreases for source hits. Neural generators of this EEG effect corresponded closely to the sources observed during encoding, localized to the middle and inferior LOC (BA 18/19; Fig. 5).

Together, these data indicate a very rapid reactivation of neural signatures established during encoding, which are visible in a power decrease in the alpha/beta frequency band. Source analysis suggests that alpha/beta decreases can be localized to the LOC, a region that is known to be constitutive for object recognition during perception and encoding (Konen and Kastner, 2008) and that is sensitive to hemisphere-specific retrieval of lateralized visual memory traces

422 (Slotnick, 2004; Slotnick and Schacter, 2006).

The very early ($\sim 100 \text{ ms}$) re-emergence of alpha/beta oscillatory decreases during 423 retrieval is in line with previous EEG studies of early reactivation (Wimber et al., 2012; Jafarpour 424 et al., 2014; Johnson et al., 2015) and suggests that retrieval correlates with a rapidly occurring 425 ecphoric process. However, it is unclear whether such early reactivations are functionally 426 relevant to successful episodic retrieval. Theoretically, these early reactivation signatures could 427 accompany memory retrieval but they might not be causally relevant to the retrieval process. To 428 429 investigate this question, we tested whether counteracting early sensory cortical activity with rTMS in the hemisphere contralateral to the site of encoding reduces retrieval of the episodic 430 memory trace. 431

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433 Counteracting early sensory cortical activity through rTMS reduces episodic memory

434 Behavioral task and procedures in Experiment 2 were identical to Experiment 1 (See Fig. 1), except that, instead of measuring EEG, rTMS and Sham stimulation were applied during the 435 retrieval phase of the experiment. Small breaks during the retrieval phases were used to relocate 436 the TMS coil for the stimulation conditions (Sham, TMS) on the different stimulation sites, left 437 hemisphere (LH) or right hemisphere (RH) in each subject. RTMS was applied at the average 438 439 center EEG frequency observed during retrieval (17.5 Hz) at the neural sources of the EEG retrieval effect obtained in Experiment 1 via a neuronavigation system (ANT-Visor; www.ant-440 neuro.com). RTMS was centered at the time interval of maximum EEG differences between 100 441 442 and 200 ms. Driving neural assemblies in the LOC at alpha/beta frequencies with 17.5 Hz rTMS (Thut et al., 2011; Hanslmayr et al., 2014) should counteract the decrease of alpha/beta power 443 observed in Experiment 1 and therefore impair episodic memory retrieval (Waldhauser et al., 444 445 2012).

As in Experiment 1, encoding condition (instructed vs non-instructed) had no effect on 446 later item recognition or source memory performance, nor did visual field at encoding (all t_{23} s < 447 1.686, $P_{\rm S} > 0.05$, see Table 1). Thus, behavioral data were again collapsed across these encoding 448 conditions. In addition, we collapsed memory performance for items for which TMS was applied 449 to the hemisphere contra- versus ipsilateral to the VF of presentation during encoding. We 450 assumed that rTMS should specifically decrease episodic memory performance for items that 451 were presented contralateral to the hemisphere of stimulation. A 2-way ANOVA on the 452 453 percentage of correct source hits on all old items revealed a significant interaction between Stimulation (Sham vs. rTMS) and Hemisphere (contralateral vs. ipsilateral to VF of presentation; 454 $F_{1,23} = 4.617$, P = 0.042, see Table 3 and Fig. 6B). No main effect for Stimulation or Hemisphere 455 456 occurred in this analysis ($F_{1,23}$ s < 3.449, Ps > 0.05). Source memory performance was

457 significantly lower when rTMS was applied at the hemisphere contralateral to the VF of encoding 458 when compared to contralateral source memory performance in the Sham condition ($t_{23} = 2.410$, 459 P = 0.024; see Table 3 and Fig. 6B). No difference between rTMS and Sham was found for 460 ipsilateral stimulation ($t_{23} = 0.160$, P = 0.874, *ns*; see Table 3 and Fig. 6B). Source hits did not 461 differ between contra- and ipsilateral hemispheres when analyzing rTMS and Sham stimulation 462 data separately (t_{23} s < 1.973, Ps > 0.05; cf. Table 3).

No main or interaction effects were obtained for item recognition as measured in hit rates, 463 regardless of source memory performance ($F_{1,23}$ s < 2.474, P_{s} > 0.05, see Table 3), suggesting that 464 rTMS only had an influence on source memory but not item memory. However, there was no 465 significant evidence ($F_{1,23} = 0.013$, P = 0.911) that rTMS affected source hits to a larger extent 466 than hits as tested in a 2 x 2 x 2 ANOVA with factors Type (source hits vs. hits), Stimulation 467 (Sham vs. rTMS) and Hemisphere (contralateral vs. ipsilateral), possibly since both measures are 468 not fully independent from each other. To further explore the nature of the rTMS effect on 469 memory several control analysis were carried out. For instance, we investigated in how far rTMS 470 introduced a response bias. To this end, we tested whether rTMS increased false alarm rates and 471 472 whether a potential effect would be dependent on the hemisphere of stimulation in a two-way repeated measures ANOVA with factors Stimulation (rTMS, Sham) and Hemisphere (LH, RH). 473 There was no significant main or interaction effect differentiating false alarm rates during LH (M 474 = 9.5 %, SD = 9.00) or RH (M = 9.1 %, SD = 4.28) rTMS and LH (M = 8.4 %, SD = 8.29) or RH 475 (M = 9.0 %, SD = 7.15) Sham stimulation (all $F_{1,23}s < 0.449, Ps > 0.05$). Second, we tested 476 477 whether rTMS increased or decreased the tendency to attribute false alarms to the visual field contralateral to the site of stimulation (see Table 3, source false alarms). Again, no significant 478 main or interaction effect emerged in the two-way repeated measures ANOVA with factors 479

480 Stimulation (rTMS vs. Sham) and Hemisphere (contralateral vs. ipsilateral; all $F_{1,23}$ s < 3.206, *P*s 481 > 0.05).

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Taken together, these analyses show that rTMS specifically affects source memory 482 performance for items previously presented in the VF contralateral to the stimulated hemisphere 483 when compared to Sham stimulation. Such an effect could not be observed for hits irrespective of 484 485 source memory performance, but the reduction in source hit performance was not significantly different from performance for hits in general. Finally, we could rule out any unspecific effect of 486 rTMS on response execution or memory bias by showing that Stimulation had no effect on the 487 endorsement of new items in terms of false alarm rates. This suggests that alpha/beta power 488 489 decreases are especially relevant for episodic memory through providing rapid sensory 490 reactivation as a basis for later source memory performance.

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Discussion

We here show that very rapid reactivation of sensory information is functionally relevant for 493 episodic memory retrieval. This conclusion is supported by the results of two independent 494 495 experiments described above. First, lateralized encoding patterns of alpha/beta power decreases re-emerge rapidly in visual cortical areas during retrieval. Second, interfering with these early 496 reactivation patterns reduces episodic memory retrieval. These findings add to the literature in 497 demonstrating very rapid, context specific memory reactivation, termed ecphory (Waldhauser et 498 al., 2012; Wimber et al., 2012; Jafarpour et al., 2014; Johnson et al., 2015). Our results go one 499 critical step beyond the previous findings in showing that these rapid reactivations of sensory 500 501 memory traces are functionally relevant for episodic memory retrieval, and directly affect the ability to retrieve contextual details of the study episode. These findings are a major conceptual 502

advance for episodic memory research, providing first evidence that ecphoric processes arecausally related to episodic memory retrieval.

Ecphory has long been suggested as a prerequisite for the 'mental time travel' implied in 505 retrieval from episodic memory (Tulving et al., 1983). It is assumed that incoming sensory 506 507 information from retrieval cues reverberates with stored memory traces, leading to their 508 immediate and involuntary reactivation (Tulving, 1982). While the theoretical idea has a long 509 tradition in cognitive psychology (Semon, 1911) and is corroborated by behavioral data (Sheldon and Moscovitch, 2010), neural evidence for this process has been sparse. Typically, neural 510 correlates of episodic memory retrieval were identified in a time range not before ~300 ms after 511 512 onset of a retrieval cue (Rugg and Curran, 2007). However, recent studies showed early reactivation patterns during episodic retrieval that are in line with our results (Waldhauser et al., 513 2012; Wimber et al., 2012; Jafarpour et al., 2014; Johnson et al., 2015). Albeit using different 514 515 analysis strategies and stimuli, these studies show that a replay of context information can occur 516 rapidly, well within 500 ms after presentation of a retrieval cue. The exact neural mechanisms of 517 this sensory reactivation and its interaction with controlled retrieval processes are still unclear 518 and deserve further investigation. According to cognitive theories, ecphory is a necessary but not sufficient prerequisite for episodic retrieval (Tulving, 1982, 1983; Moscovitch, 2008). The 519 sensory information needs to be further processed by higher retrieval mechanisms, possibly 520 through hippocampal-neocortical loops (Horner et al., 2012; Staresina et al., 2012) and 521 potentially guided by prefrontal and parietal control (Ranganath and Paller, 1999; Cabeza et al., 522 523 2008). As our data suggest, disrupting early sensory reactivation via external stimulation negatively affects the recollection (i.e. retrieval of contextual details) of episodic memories. 524 Interestingly, our results match closely with one of our earlier studies that showed that inhibiting 525 526 retrieval of interfering information leads to an increase in alpha/beta oscillatory power in the

hemisphere housing unwanted memory traces that interfere with the retrieval of a target memory
trace (Waldhauser et al., 2012). This suggests that early modulations of alpha/beta power are a
decisive ingredient of successful remembering and can already act in concert with retrieval goals
and be biased by higher order cognitive control mechanisms.

Discussing the possible involvement of prefrontal control processes calls into question 531 532 whether 'ecphory' is the right label for the early sensory reactivation effects observed in the 533 present data. However, as already mentioned in early papers on this topic, higher-order control mechanisms are likely to interact with rapid sensory reactivation during ecphory (Tulving et al., 534 1983; Johnson, 1992; Lepage et al., 2000; Rugg and Wilding, 2000). Recent neuroscientific 535 536 studies also suggest that it is difficult to view these processes in separation, even at early stages of memory processing and during involuntary retrieval (Kompus, 2011; Kompus et al., 2011; 537 Waldhauser et al., 2012). 538

In line with our hypothesis, a decrease of alpha/beta oscillatory power at the hemisphere 539 contralateral to the VF of encoding was most pronounced for source hits, to the extent that single 540 trials could be classified as source hits or source misses on the basis of EEG lateralization. In the 541 542 same vein, rTMS had a selective influence on source memory performance (albeit not to the extent of yielding significant differences between source hits, and hits, i.e. item memory). This 543 pattern of results suggests that alpha/beta power decreases are particularly relevant for source 544 memory performance, which is in accordance with the theoretical notion of ecphory, because 545 correct source memory judgments require the highest amount of ecphoric information (Tulving et 546 547 al., 1983). Unexpectedly, in the EEG analysis, source misses showed alpha/beta lateralization in the opposite direction compared to source hits. Interpretation of this result has to remain 548 speculative at this point. It appears that visual cortical activity predicted later memory decisions, 549 550 such that a retrieved memory representation is attributed to the VF contralateral to the

hemisphere where a decrease of alpha/beta power occurred. It could be the case that memory 551 552 representations attributed to the wrong VF were initially stored in the ipsilateral hemisphere during encoding. Alternatively, this misattribution may be due to non-systematic fluctuations in 553 alpha/beta activity that led to illusory recollection of the wrong hemifield (e.g., Lange et al., 554 555 2014). Finally, it might be the case that EEG lateralization in general reflects a process of source 556 reconstruction, and not sensory reactivation. However, this possibility seems rather unlikely, 557 since reconstructive processes during memory retrieval are more effortful and typically observed later (> 600 ms) during retrieval processing (Johansson and Mecklinger, 2003; Herron, 2007). 558 Future studies, possibly combining EEG and high-resolution fMRI or using electrophysiological 559 560 methods that allow for assessing gamma oscillations (see below), might allow to distinguish between true versus false source memories in this paradigm (Slotnick and Schacter, 2004; 561 Sederberg et al., 2007). 562

563 Our findings are in line with the idea that alpha/beta power decreases reflect sensory information of episodic memory traces (Hanslmayr et al., 2012). However, we cannot conclude 564 that these are the only frequency bands that are involved in ecphoric processing since we 565 566 restrained analyses to low frequencies up to 30 Hz because EEG is not ideally suited to pick up the presumably very local high-frequency activities in the gamma range (da Silva, 2013). 567 Furthermore, we restrained rTMS to the center frequency of the alpha/beta range observed in 568 Experiment 1 but did not apply stimulation with another frequency. Thus, although we have 569 strong reason to assume that alpha/beta power in visual cortex plays a decisive role for ecphoric 570 571 processes, we cannot conclude that ecphory is specific to the alpha/beta range. It might be that gamma together with theta and alpha oscillations also play a decisive role in ecphoric processes 572 (Osipova et al., 2006; Osipova et al., 2008). These are important questions that are beyond the 573 574 scope of our study and should be addressed by future studies using techniques that allow for

investigating these high-frequency activities (MEG or intracranial EEG) and applying different 575 576 control frequencies in stimulation protocols (using TMS or transcranial alternating current stimulation). Another interesting question that is beyond the scope of our study is the role of 577 hippocampal-neocortical interactions during early retrieval processes. For instance, does the rapid 578 579 reactivation of sensory information depend on the hippocampus or is it a purely cortical or thalamo-cortical phenomenon (Staudigl et al., 2012; Headley and Weinberger, 2015; Ketz et al., 580 581 2015)? Our results add an important angle to this research topic by suggesting that the earliest interactions between sensory information and stored memory traces may occur in the alpha/beta 582 oscillatory band, beyond the long-discussed role of theta and gamma oscillations for memory 583 processing. Finally, another open question is whether similar results would be observed in 584 585 different sensory modalities, or with different visual stimuli. Future studies, together with past research using different stimulus material and different experimental manipulations are required 586 587 to generalize our findings (Gratton et al., 1997; Wheeler and Buckner, 2003; Slotnick and Schacter, 2006; Waldhauser et al., 2012). 588

Together, our results show that retrieval from episodic memory leads to a very rapid 589 590 reactivation of encoding activity which is visible in alpha/beta power decreases in visual brain regions. Affecting the cortical generators of the alpha/beta power decrease with rTMS in the 591 same frequency range hampered episodic memory retrieval. These observations suggest that 592 593 episodic memory retrieval relies on ecphoric processes. A deeper understanding of ecphory and its manipulation with cortical stimulation techniques potentially offers new perspectives for the 594 595 treatment of neuropsychiatric disorders (McNamara et al., 2001). For example, patients suffering 596 from posttraumatic stress disorder suffer from the rapid intrusive reactivation of sensory memories pertaining to their traumatic experiences (Reynolds and Brewin, 1999). Treating 597

- 598 memory intrusion through the external induction of oscillatory activity could be an important
- 599 future therapeutic mean to assist patients in controlling unwanted memories.

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Table Legends 743 744 **Table 1.** Percentages of hits and source hits $(M \pm SEM)$ did not differ between VF (LVF and RVF) or Instruction (Instructed vs. Non-instructed) at encoding (see Results). 745 **Table 2.** Contingency between lateralization index (contra- minus ipsilateral power; LI) and 746 747 source memory performance as observed absolute frequencies across all single trials of all subjects (expected values calculated in a χ^2 -test are given in parentheses). LI < 0 signifies an 748 alpha/beta power decrease at the electrode cluster contralateral to the VF of encoding, as 749 hypothesized for source hits, whereas LI > 0 signifies an ipsilateral decrease in the 100-200 ms 750 time window. 751 752 **Table 3.** Percentages of hits, source hits and source false alarms ($M \pm SEM$) depending on Stimulation (Sham vs. rTMS) and Hemisphere (Contra- vs. Ipsilateral). 753 754 **Figure Legends** 755 Figure 1. Posterior electrodes selected for analysis at encoding. Lateral electrodes selected for 756 the initial sliding cluster statistic are depicted in large broken (LH) and dotted (RH) circles. In the 757 topograhical cluster analysis comparing LVF and RVF condition, central electrodes (large solid 758 black) were also included. 759 Figure 2. Experimental procedure for Experiments 1 and 2. Pictures of everyday objects were 760 presented to the left or right of fixation at encoding, followed by a response task according to 761 encoding condition (instructed versus non-instructed). Instructed encoding required participants 762 763 to intentionally encode the presented object and to judge the difficulty to do so. For noninstructed encoding, participants were requested to estimate whether the depicted object would fit 764 into a shoebox or not. During retrieval, all previously shown old items were presented together 765 766 with the same amount of previously unseen new items. All pictures were shown at the center of

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the screen to isolate lateralized cortical activity to the reactivation of sensory memory traces
established during encoding. An old/new item recognition task was followed by a source memory
task, asking for the VF at presentation. The whole procedure was carried out twice in each
subject, once with instructed, once with non-instructed encoding. In Experiment 1, EEG was
measured throughout the experiment. In Experiment 2, rTMS and Sham was applied to the left or
right cortical hemisphere during retrieval, switching between these stimulation conditions every
40 trials.

Figure 3. EEG activity in Experiment 1 at sensor level. A: Encoding effects. Top: FDR-corrected 774 results of the sliding cluster statistic, thresholded at $P_{adj} < 0.05$, indicating significant power 775 776 differences between LVF and RVF conditions at respective posterior contralateral sensors (cf. 777 Fig. S2) between 200-700 ms and 8-20 Hz (boxed white). Center: LVF-RVF power differences in the selected time-frequency window. Significant electrode clusters interacting with VF condition 778 779 indicated by black (left hemisphere) and white (right hemisphere) circles. Bottom: Mean power at the left-hemsipheric (LH) and right-hemispheric (RH) electrode clusters interaction with VF 780 condition (LVF and RVF). Error bars signify ±SEM. B: Retrieval effects. Top: Mean difference 781 782 between contra- and ipsilateral EEG power for both VF conditions at the LH and RH electrode clusters identified at encoding, showing a contralateral power decrease between 100-200 ms and 783 10-25 Hz, thresholded at P < 0.05 (Wilcoxon sign rank test). The analysis focused on the time 784 window preceding recollection effects (< 500 ms; post-recollection time window masked grey). 785 Center: LVF-RVF power differences in the selected time-frequency window. Black (left 786 787 hemisphere) and white (right hemisphere) circles represent electrode clusters identified during encoding. Bottom: Mean power at the left-hemsipheric (LH) and right-hemispheric (RH) 788 electrode clusters identified at encoding, interacting with VF condition (LVF and RVF). Error 789 790 bars signify \pm SEM.

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Figure 4. Hemisphere-specific effects for the LVF-RVF comparison: A: Time-frequency
representation of the LVF-RVF difference for left (red circles) and right (blue circles)
hemispheric electrode clusters. The 100-200 ms time-window selected on the basis of the running
Wilcoxon-Test (Fig. 3B, top) is boxed black (LH) or white (RH). B: Mean difference between
LVF and RVF conditions at left and right hemispheric clusters between 100-200 ms at the
hemisphere-specific peak frequencies (10 and 20 Hz). Note that only the LH cluster shows a
significant difference between VF conditions at 10 Hz, whereas effects for the RH cluster are
more pronounced at higher frequencies, peaking at 20 Hz. Error bars signify ±SEM. Significant
(P < 0.05) differences are marked by asterisks.
Figure 5. Cortical sources of EEG power differences between LVF and RVF conditions and
between contra- and ipsilateral hemispheres at encoding (8-20 Hz, 200-700 ms, green) and
retrieval (10-25 Hz, 100-200 ms, blue). Interhemispheric differences are backprojected to the

cortical hemispheres, reflecting corresponding voxels in each hemisphere. Depicted *t*-values are

thresholded at P < 0.01, with maximum values reflecting interhemispheric LVF-RVF differences at *P* < 0.0005.

Figure 6. A: Schematic depiction of rTMS stimulation in the retrieval trial procedure of

Experiment 2 at the left (red) and right (green) maximum cortical source (MNI coordinates: ± 40 ,

-78, 0) of 10-25 Hz (100-200 ms) interhemispheric LVF-RVF differences at retrieval as

identified in Experiment 1. B: Behavioral results from Experiment 2, showing the difference

between TMS-Sham condition effects on source memory performance for items presented in the

contra- and ipsilateral VF during encoding. Error bars signify \pm SEM. Significant (P < 0.05)

effects are marked by asterisks.

Table 1

	Experiment 1				Experiment 2			
	Instructed	Non- instructed	LVF	RVF	Instructed	Non- instructed	LVF	RVF
Hits	67.9 ±	71.3 ±	71.2 ±	$68.0 \pm$	$69.7 \pm$	$72.0 \pm$	$69.4 \pm$	73.3 ±
TIIts	3.35	1.45	2.25	2.76	2.48	2.81	2.71	2.51
Source	55.7 ±	50.3 ±	53.1 ±	52.9 ±	$56.8 \pm$	52.0 ±	$54.0 \pm$	55.9±
Hits	4.01	2.31	2.95	2.96	2.90	3.03	2.85	2.91

Memory Performance Depending on Encoding Condition in Experiments 1 and 2.

Table 2

	LI < 0	FI > 0
Source hits	470 (454)	427 (443)
Source misses	123 (139)	151 (135)

Contingency between Source Memory Performance and EEG Lateralization in All Single Trials

Table 3

-		*TN		Shom		
		111	15	Snam		
		Contralateral	Ipsilateral	Contralateral	Ipsilateral	
-	Source Hits	51.7 ± 2.82	54.6 ± 2.61	58.8 ± 3.22	54.9 ± 3.07	
	Hits 69.2 ± 2.61		70.5 ± 2.43	75.3 ± 3.34	70.3 ± 3.15	
	Source FA	$4.0\ \pm 0.55$	4.1 ± 0.53	5.3 ± 0.97	3.4 ± 0.52	
823						
824						
825						
826						

Memory Performance Depending on Stimulation and Hemisphere in Experiment 2.









Source localization results



A TMS stimulation



Contralateral

Ipsilateral

TMS stimulation - Sham