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9 **Current directions in visual working memory research: an introduction and emerging insights**

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Abstract

Visual working memory (VWM) is a core construct in the cognitive (neuro-)sciences, assumed to serve as a hub for information exchange and thus supporting a multitude of cognitive functions related to processing visual information. Here, we give an introduction into key terms and paradigms and an overview of ongoing debates in the field, to which the articles collected in this Special Issue on “Current Directions in Visual Working Memory Research” contribute. Our aim is to extract, from this overview, some ‘emerging’ theoretical insights concerning questions such as the optimal way to examine VWM, which types of mental representations contribute to performance on VMW tasks, and how VWM keeps features from the same object together and apart from features of concurrently maintained objects (the binding problem).

Keywords: visual cognition, working memory, attention, binding, interference

1 Current directions in visual working memory research: an introduction and emerging insights

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3 Visual working memory (VWM) – the mental workspace for the temporary storage and manipulation
4 of visual information – is a central cognitive faculty at the interface between visual perception and goal-
5 directed action. It is pivotal for making sense of the constantly changing stream of information arriving
6 through the visual system: Objects move, our eyes move, our body moves, even the whole world may
7 appear to move (such as on a merry-go-round). To keep track of agents and things in this rapid flow, it is
8 crucial to maintain and match representations of relevant visual objects across all these changes (Aagten-
9 Murphy & Bays, 2019; Cronin & Irwin, 2018). But beyond holding visual information passively (a
10 function implied by the term ‘memory’), VWM is thought to be a general-purpose visual representation
11 system that is involved in a multitude of cognitive functions requiring the (active) processing of currently
12 available visual information in order to achieve the goals of the task at hand (Luck & Vogel, 2013;
13 Zimmer, 2008). Reflecting its importance as a central cognitive hub and its relation to many crucial
14 cognitive functions (Fukuda, Vogel, Mayr, & Awh, 2010; Unsworth, Fukuda, Awh, & Vogel, 2014),
15 VWM has developed, over the past decades, into a core topic in the cognitive (neuro-)sciences, sparking
16 an abundance of theoretical and methodological advances that range from general models of cognition and
17 consciousness (Block, 2011; Bundesen, Habekost, & Kyllingsbaek, 2005, 2011; Dehaene, & Naccache,
18 2001; Schneider, 2013; Soto & Silvanto, 2016; Usher, Bronfman, Talmor, Jacobson, & Eitam, 2018) to
19 the trial-wise decoding of specific mental contents from neuroimaging data (*brain reading*; Christophel,
20 Klink, Spitzer, Roelfsema, & Haynes, 2017; Harrison & Tong, 2009; Serences, Ester, Vogel, & Awh,
21 2009; Sprague, Ester, & Serences, 2014).

22 On this background, in July 2017, we hosted an international symposium on VWM at Ludwig-
23 Maximilians-University Munich, which aimed to bring together a select group of experts representing
24 different theoretical stances and methodological approaches in this rapidly growing field. Our intention
25 was to foster scientific exchange and discussions across the various viewpoints and help identify the most
26 urgent and promising questions for future research. The result did meet, if not exceed, our high

1 expectations. To make (at least some of) the spirit of this symposium available to a broader audience, we
2 decided to edit the present special issue, featuring work from many participants of the symposium as well
3 as a select number of experts who could not attend at the time. What we, hopefully, have achieved is a
4 representative, state-of-the-art overview of the field, spanning many of the various viewpoints and
5 currently debated issues.

6 To put the collection of articles into context, in particular (though not only) for readers less familiar
7 with the vibrant research on VWM, we go on to provide a selective overview on the history of the field
8 and the experimental paradigms and theoretical issues that drove and continue to drive much of the
9 research. As detailed below, all articles in the present issue, in one way or another, relate to these various
10 lines of ideas and the respective debates.

11 Most strands of psychological investigation start off with beautiful simplicity, but become more
12 complex and seemingly ‘unwieldy’ as research progresses. VWM research is no exception to this.
13 Originally, there was broad consensus that VWM could hold some four bound objects stored in separate
14 slots (Luck & Vogel, 1997), that the usage of VWM slots could be accurately tracked via neuronal
15 markers (Todd & Marois, 2004; Vogel & Machizawa, 2004), and that performance on the standardly used
16 *change-detection task* (Pashler, 1988) purely reflects VWM functioning, free of any extraneous factors
17 (Cowan, 2001).

18 In the (one-shot, whole-display) change-detection task, several objects (most often: coloured squares)
19 are briefly presented in a first (memory) display and after a short retention interval (typically ~1 s), a
20 second (test) display is shown. The second display is identical to the first in one half of randomly inter-
21 mixed trials, but in the other half one object has changed (typically its colour). Participants’ task is to
22 decide whether a change was present or not. A simple formula can be applied to calculate, from the
23 observed error pattern, the number of objects a given participant can maintain in VWM (k ; Pashler, 1988;
24 Rouder, Morey, Morey, & Cowan, 2011). Performance on this task was – in contrast to previous, largely
25 verbal, working-memory research – considered to be free from confounding influences such as long-term
26 memory and response interference, and, as all information was available in one ‘snapshot’, there was no

1 reason to treat the various objects differently (Cowan, 2001). However, subsequent research inspired by
2 these initial findings resulted in the accumulation of ever more data that was not easily reconcilable with
3 these initial assumptions and the original, simple theory.

4 For instance, the assumption that bound objects are held in VWM was supported by a series of
5 carefully executed change-detection experiments showing that any number of features could be stored for
6 each object with no additional costs for additional features (Luck & Vogel, 1997). This strong assumption
7 was soon challenged by studies that observed a clear decrease in performance as the number of features
8 per object increased. First, costs were shown for features from the same feature dimension (e.g., Olson &
9 Jiang, 2002; Wheeler & Treisman, 2002), for increasing object complexity (Alvarez & Cavanagh, 2004),
10 and for assigning features to different parts of the same object (Xu, 2002). Further research revealed costs
11 even for features from different dimensions on the same simple-object part (Fougnie, Asplund, & Marois,
12 2010). The broadest consensus at present appears to be that, although there is some *object benefit* (i.e.,
13 more information can be stored when it is distributed across fewer objects, likely due to the features of an
14 object sharing the same location), storing additional features is not cost-free (Fougnie, Cormiea, &
15 Alvarez, 2013).

16 Whether costly or not, the brain often has to code multiple features of an object and, additionally,
17 information on which features belongs to which object (Treisman, 1996; Treisman & Gelade, 1980). This
18 *binding problem* is a recurrent theme in working-memory research and the present special issue. In their
19 contribution, Schneegans and Bays (2019) give a comprehensive overview of the binding problem in
20 visual working memory and how this problem might be solved on the neuronal level. They conclude that
21 both object benefits and costs of storing additional features can be explained by noisy, distributed VWM
22 representations of features, and that it is unnecessary to postulate a separate resource for binding features
23 within an object. Instead, features might be bound by default via their common position in space
24 (Schneegans & Bays, 2017) or time (most likely, ordinal position; Oberauer, Lewandowsky, Farrell,
25 Jarrold, & Greaves, 2012; Swan & Wyble, 2014). Whether space or time is used for binding features is not
26 easily distinguishable: when objects are presented concurrently at different positions, space can be

1 remapped onto time by sequential attention allocations (Zimmer & Liesefeld, 2011); and when objects are
2 presented sequentially at the same location, time can be remapped onto space by internally assigning
3 objects to different unoccupied locations (Abrahamse, Van Dijck, Majerus, & Fias, 2014; see also
4 Oberauer, 2009). Another hotly debated question concerns whether VWM capacity is actually limited by
5 *slots* or rather by a continuous, infinitely divisible *resource* (Bays & Husain, 2008). Schneegans and Bays
6 favour the latter assumption and explain this limit in terms of representational noise (see also Oberauer &
7 Lin, 2017; Wilken & Ma, 2004)

8 The slots-vs.-resource debate was largely based on data from a new procedure that can provide a
9 more fine-grained picture of VWM performance than the classical change-detection task: Instead of
10 comparing the memory display to a second test display, the *continuous-report task* requires participants to
11 reproduce an object feature chosen from a (virtually) continuous circular space (e.g., by choosing the
12 colour of a probed object from a colour wheel; Wilken & Ma, 2004; Zhang & Luck, 2008; or by adjusting
13 a probe object, e.g., Bays, Wu, & Husain, 2011). This task is also referred to as *analogue/cued-recall* or
14 *delayed-estimation task*. In contrast to the change-detection task, the continuous-report task does not
15 provide a binary outcome on each trial (correct vs. incorrect response), but a (virtually) continuous
16 measure: the distance between the correct feature value and the actual response (*estimation error*). Zhang
17 and Luck (2008) proposed to analyse data in this task by fitting a mixture of a van Mises (the circular
18 equivalent of a Gaussian) and a uniform distribution to the distribution of estimation errors and
19 interpreting this model's parameter values. This *mixture model* neatly fits the typically observed error
20 distribution and has since been ubiquitously applied to continuous-report data. However, several
21 arguments against the use of the mixture model have been raised (see, in particular, Ma, 2019), so that it is
22 probably advisable to analyse raw estimation errors (in addition) or to apply more elaborate, mechanistic
23 models of performance on the continuous-report task (e.g., Oberauer & Lin, 2017; Schneegans & Bays,
24 2017; Swan & Wyble, 2004).

25 Various neuronal correlates of VWM representations have been proposed. Early research identified
26 activity in/over parietal areas as measured by EEG contralateral to the remembered items (*contralateral*

1 *delay activity*, CDA; Vogel & Machizawa, 2004; for a recent review, see Luria, Balaban, Awh, & Vogel,
2 2016) or by fMRI (Todd & Marois, 2004; Xu & Chun, 2006) as a potential neuronal correlate of VWM
3 maintenance. Subsequent studies decoded VWM content from early visual areas (Harrison & Tong, 2009;
4 Serences et al., 2009). It turned out that decoding VWM content is possible from many areas throughout
5 the human brain (for a recent review, see Christophel et al, 2017). As concurrent and partially overlapping
6 activation of several neuronal populations would make it impossible to decide which features belong to
7 which objects (the binding problem), it was speculated that VWM-related parietal activity reflects a
8 pointer system, with each pointer connecting all features of one object. Indeed, the parietal activity does
9 not appear to be specific to the maintenance of visual information after it is gone; rather, it also reflects
10 processing of physically available information in VWM (Drew & Vogel, 2008; Tsubomi, Fukuda,
11 Watanabe, & Vogel, 2013).

12 As another – neuronally inspired – potential solution to the binding problem, Lisman and colleagues
13 proposed that objects are differentiated in time by differential temporal spiking patterns (Lisman &
14 Jensen, 2013; Lisman & Idiart, 1995; but see Schneegans & Bays, 2019). Neurons coding a certain feature
15 fire at a high frequency (gamma, i.e. > 30 Hz), with different representations (gamma cycles) being locked
16 to different phases of a theta cycle (i.e., 4-7 Hz). In other words, each item in VWM is repeatedly
17 reactivated (gamma) in a given order (theta). Accordingly, the coupling of gamma and theta phase has
18 been explored as a neuronal marker of VWM maintenance (Sauseng et al., 2009), and this idea was used
19 to explain capacity limits and the (purported) slot-like fashion of VWM storage: VWM capacity is limited
20 by the number of complete gamma waves that can be nested within a theta cycle of a given length.
21 Alternatively, according to a more recent proposal, items are coded as gamma bursts (i.e., multiple cycles;
22 Herman, Lundqvist, & Lansner, 2013; Van Vugt, Chakravarthi, & Lachaux, 2014) and only one item is
23 coded per theta period, with different items being refreshed in consecutive theta cycles. During a theta
24 cycle, gamma amplitude first increases and then decreases, yielding a coupling of gamma amplitude to
25 theta phase. In their contribution to the special issue, Sauseng, Peylo, Biel, Friedrich and Romberg-Taylor
26 (2019) review the pertinent cross-frequency-coupling literature and suggest that the more recent version of

1 this theory (Herman et al., 2013) and a newly proposed alternative are compatible with continuous-
2 resource as well as fixed-slots conceptions of VWM capacity. In particular, they argue that some
3 flexibility in the length of theta and/or gamma cycles yields flexibility in the number and precision of
4 VWM representations.

5 Much research has shown that not all VWM representations are created equal, and that
6 representational quality varies considerably across trials and objects (Fougnie, Suchow, & Alvarez, 2012;
7 van den Berg, Shin, Chou, George, & Ma, 2012). In their contribution to the special issue, Czoschke,
8 Fischer, Beitner, Kaiser, and Bledowski (2019) examine two sources of this variability: processing objects
9 on the previous trial(s) and processing other objects on the current trial. With a sequential presentation of
10 two objects per trial, they observe that VWM representations are attracted towards the last item on the
11 previous trial and repulsed away from the preceding item on the same trial. These effects might reflect
12 mechanisms contributing to the separation and integration of information across objects and episodes.

13 In their contribution to the special issue, Bae and Luck (2019) examine how representing a single
14 item in VWM is affected by performing a simple task during maintenance. They combine the continuous-
15 report task with the classical dual-task interference paradigm that dominated the working-memory
16 literature before research on VWM gained momentum (Baddeley, 1986; Logie, 1995). In this paradigm,
17 participants have to perform a secondary task during working-memory maintenance, which is supposed to
18 either draw or not draw on the same working-memory system or component. Bae and Luck's results show
19 that processing a letter deteriorates the representation of a single orientation, in that it becomes less precise
20 and biased more strongly away from cardinal orientations (see also Hardman, Vergauwe, & Ricker, 2017).
21 No such effect is found for processing an auditory stimulus during single-orientation maintenance. This
22 dissociation indicates that processing information from the same modality displaces the VWM object from
23 a special state ('focus of attention', see Oberauer, 2002; Oberauer & Lin, 2017), leaving only a relatively
24 coarse representation. Having to remember only one item on each trial is critical in this study, because this
25 rules out interference from other items on the same trial. Bae and Luck's study also nicely demonstrates a
26 major strength of the continuous-report task: it provides a particularly sensitive measure of subtle effects

1 on VWM performance. Remembering only one object would produce ceiling performance in the change-
2 detection task, making it impossible to examine effects on the representation of a single item.

3 In their contribution to the special issue, Tabi, Husain and Manohar (2019) demonstrate a drawback
4 of a standard version of the continuous-report task, which requires participants to adjust a memory probe:
5 performance improves if the probe object is initially set to neutral with respect to the probed feature,
6 instead of taking a random feature value as is common practice in this paradigm. Thus, processing the
7 random probe feature likely partially overwrites the probed memory representation. A similar interference
8 is likely induced by the commonly employed colour wheel (Souza, Rerko, & Oberauer, 2016). Tabi et
9 al.'s new method to start off with a neutral probe is designed to eliminate this source of interference by
10 allowing participants to first transfer the probed feature into a more robust state (see Souza et al., 2016, for
11 a related effect of retro-cues, i.e., cues given during the retention period before the test).

12 Probably, such interference does not occur in the change-detection task. One potential interpretation
13 of the whole-display change-detection task is that the onset of the test display produces a spatial
14 representation akin to a saliency map in visual search that (noisily) encodes the mismatch with the
15 memorized display, with registration of a mismatch signal being used to decide upon the presence of a
16 change (Hyun, Woodman, Vogel, Hollingworth, & Luck, 2009; Liesefeld, Liesefeld, Müller, & Rangelov,
17 2017). On that account, the interference by the test display would occur only after the critical mismatch
18 signal is already produced, so that the change-detection task would indeed provide a relatively pure (albeit
19 coarse) picture of VWM performance (but see, Alvarez & Thompson, 2009).

20 A further advantage of the change-detection task is that, in addition to accuracy, it allows reaction
21 time to be examined as a measure of the speed of comparing VWM entries with visual input (Donkin,
22 Nosofsky, Gold, & Shiffrin, 2013; Gilchrist & Cowan; Hyun et al., 2009; Liesefeld et al., 2017; Park,
23 Zhang, & Hyun, 2017). The interpretation of reaction times is less straight-forward in the continuous-
24 report task, because it takes quite some time until a response is selected and executed (moving the arrow
25 to the position on the colour wheel or toggling through all values with the probe), allowing for all kinds of
26 confounding influences and measurement noise (see, e.g., Tabi et al., 2019). Thus, the two tasks have

1 complementary strengths and weaknesses and can provide different perspectives on VWM performance,
2 and comprehensive models of VWM should explain performance on both (and other, e.g., localization,
3 Liesefeld, Liesefeld, & Müller, 2019; van den Berg et al., 2012) tasks.

4 An (unwanted) source of variability in all types of VWM tasks arises from the possibility that people
5 do (at times) not only represent individual objects, but (additionally) what several objects in the display
6 have in common. This might include maintaining chunks of information (Miller, 1957; Morey, Cong,
7 Zheng, Price, & Morey, 2015; Peterson & Berryhill, 2013; Quinlan & Cohen, 2012) or ensemble
8 representations (Brady & Alvarez, 2011, 2015a,b; Brady & Tenenbaum, 2013). In the classical colour
9 change-detection task, repetition of colours within a display provides opportunities for such compressed
10 representations. In her contribution to the special issue, Morey (2019) directly manipulated the potential
11 for compression by presenting up to three objects of the same colour. She observed increased detection
12 rates for these redundant objects and also – in young, but less so in older adults – a spill-over of VWM
13 capacity to objects with unique colours. Furthermore, using pupil dilation as a marker of mental effort, she
14 found decreased effort with increasing redundancy in young participants.

15 In our contribution to the special issue (Liesefeld et al., 2019), we tried to minimize opportunities for
16 compressed coding by explicitly avoiding colour repetitions within a display. Still, even in this purest
17 version of the standard colour change-detection task, we find indications for the involvement of ensemble
18 representations. In particular, we additionally asked participants to localize the change and compared
19 localization performance to change-detection performance using mathematical models. The model
20 providing the best account of our data indicates that VWM capacity is routinely overestimated when
21 considering only change-detection performance and that VWM can actually hold only about 2.3 individual
22 items, which contrasts with earlier estimates of 7 ± 2 (Miller, 1957) or, respectively, 4 ± 1 (Cowan, 2001)
23 items. Given that a privileged, focal-attentional state (Bae & Luck, 2019; Oberauer, 2002; Oberauer &
24 Lin, 2017) holds 1 of these 2.3 items, the capacity estimate for ‘usual’ VWM would effectively shrink to
25 (a little over) 1 item.

1 Speculations about multiple, qualitatively different VWM states (see also Cowan, 1999; Oberauer,
2 2002) prompt another potential solution to the binding problem (or rather its dissolution). If ‘usual’ VWM
3 indeed can hold only one item, one item is in the focus of attention, and any additional information is
4 coded as an ensemble, one needs to assume only one representation in each state to explain typical
5 estimates of VWM capacity of around 3 items. Consequently, there is no further need to keep features
6 from an object bound together and apart from other objects. The notion that a multitude of qualitatively
7 different representations, at different levels of abstraction, contribute to performance on VWM tasks
8 would be in line with recent neuroimaging evidence for VWM representations in several, distributed brain
9 areas (Christophel et al., 2017). The ever-increasing list of contributors to performance on VWM tasks
10 also hints at a general “problem” in cognitive science: humans are highly adaptive and exploit whatever
11 cognitive resources they have at their disposal to solve a given (laboratory) task without regard to the (by
12 the scientist) targeted cognitive construct and the aesthetically pleasing simplicity of cognitive theories
13 (see also Zimmer & Liesefeld, 2011).

14 Not only does attention affect VWM performance (by raising one item to a special state; Griffin &
15 Nobre, 2003; Oberauer, 2002; Oberauer & Lin, 2017; Souza & Oberauer, 2016), but VWM is also thought
16 to influence attentional dynamics. One common assumption is that an item in the special state operates as
17 a *search template* (Duncan & Humphreys, 1989; Hollingworth & Hwang, 2013; Olivers, Peters,
18 Houtkamp, & Roelfsema, 2011; Schneider, 2013). In their contribution to the special issue, Berggren and
19 Eimer (2019) examine how storing shapes in VWM conflicts with spatial templates (i.e., maintenance of
20 potential target locations). Using an electrophysiological marker of attention allocations (N2pc; Eimer,
21 1996; Luck & Hillyard, 1994a,b), they observe a delay in attention allocation towards the target when
22 VWM load is high, indicating that VWM for shapes and spatial templates share a common resource.

23 Working memory also appears to be involved in the familiarization with visual-search scenes. It has
24 been shown that repeating spatial stimulus configurations (‘context’) speeds up the search due to
25 incidental long-term learning of spatial distractor-to-target relations (*contextual cueing*). In his
26 contribution, Pollmann (2019) reviews the literature on the involvement of spatial working memory in the

1 contextual-cueing effect. Various studies have shown that spatial working-memory load can disrupt the
2 effect. This is, however, true only if applied during the test phase of the task, indicating that spatial
3 working-memory load does not impede the acquisition of contextual information; rather, the retrieval of
4 this information from long-term memory operates via working memory and may thus be hampered by
5 spatial working-memory load. In their contribution, Annac, Zang, Müller and Geyer (2019) report that this
6 is not necessarily the case: the working-memory bottleneck can be bypassed as a result of training. That is,
7 after an extended period of training, the contextual-cueing effect was found to emerge even with
8 concurrent working-memory load during test. Surprisingly, Annac et al. even observed an amplification of
9 the contextual-cueing effect by concurrent working-memory load, indicating that, under these conditions,
10 context information may be directly retrieved from long-term memory (see Reinhart, McClenahan, &
11 Woodman, 2016, for a related finding).

12 Another core topic in VWM research are interindividual differences in VWM capacity and whether
13 capacity is fixed or can be boosted (Fukuda et al., 2010; Liesefeld, Liesefeld, & Zimmer, 2014; Unsworth
14 et al., 2014; Vogel & Machizawa, 2005; Vogel et al., 2005). Sauseng et al.'s (2019) review discussed
15 above summarizes evidence that entrainment of certain theta frequencies via electrical cortical stimulation
16 can increase (slower theta) or decrease (higher theta) VWM capacity (Vosskuhl, Huster, & Hermann,
17 2015; Wolinski, Cooper, Sauseng, & Romei, 2018). But we don't need to turn to cortical stimulation to
18 improve VWM performance. In their contribution to the special issue, Dodwell, Müller and Töllner (2019)
19 examine how moderate aerobic exercise (vs. passive control) and body posture (upright on a treadmill vs.
20 seated on a bike) while performing a speeded VWM task influence separable VWM processes. Exercise
21 and upright posture speeded reaction times compared to passive (resting) and seated conditions,
22 respectively. Examination of electrophysiological markers revealed that this reaction-time advantage was
23 not due to faster VWM access, but rather to expedited processes of selecting the appropriate response to
24 the target representation held in VWM.

25 Finally, the relation between stimulus material and the observer, such as familiarity (Curby &
26 Gauthier, 2007; Curby, Glazek, & Gauthier, 2009; Jackson & Raymond, 2008) and emotional content

1 (Jackson, Linden, & Raymond, 2014; Jackson, Wu, Linden, & Raymond, 2009; Kensinger & Corkin,
2 2003; Maran, Sachse, & Furtner, 2015; Mather, 2007), also influences VWM performance. In their
3 contribution, Curby et al. (2019) report a detrimental effect of fearful faces on VWM capacity that is
4 consistent across four experiments. This is particularly notable, as earlier research had more often found
5 VWM benefits, rather than costs, for emotional (including fearful, angry, sad, and happy) faces (e.g.,
6 Jackson et al., 2009, 2014; Sessa, Luria, Gotler, Jolicoeur, & Dell'acqua, 2011). Curby et al. test and
7 discuss in great detail how effects of emotion on VWM performance are modulated by subtle differences
8 in task designs (such as encoding duration and set size) and/or by the processing and maintenance of
9 different emotions.

10 The collection of articles is rounded off by an integrative commentary by Rhodes and Cowan (2019)
11 that we have not yet received at the time of writing this introduction. It will be of interest to the reader to
12 compare the overlap of our introduction with their commentary.

13 Although some current topics, such as the active manipulation of VWM content (e.g., Christophel,
14 Cichy, Hebart, & Haynes, 2015; Liesefeld & Zimmer, 2013) and the relationship of LTM and VWM (e.g.,
15 Brady, Störmer, & Alvarez, 2016; Schurgin, Cunningham, Egeth, & Brady, 2018) are not represented
16 here, we believe that reading through the articles in this issue provides a relatively comprehensive
17 overview on the current state of VWM research. In any case, we are proud to present this collection of
18 articles to the readers of the *British Journal of Psychology* and thank the editor-in-chief, Stefan
19 Schweinberger, for giving us the opportunity to compile this Special Issue. We hope that you all enjoy
20 reading it as much as we enjoyed putting it together!

21 **References**

22 Aagten-Murphy, D., & Bays, P. M. (2019). Functions of memory across saccadic eye movements. In: T.
23 Hodgson (Ed.), *Processes of Visuo-spatial Attention and Working Memory. Current Topics in*
24 *Behavioral Neurosciences*. Berlin, Heidelberg: Springer. Advance online publication.
25 doi:10.1007/7854_2018_66

- 1 Abrahamse, E., van Dijck, J.-P., Majerus, S., & Fias, W. (2014). Finding the answer in space: The mental
2 whiteboard hypothesis on serial order in working memory. *Frontiers in Human Neuroscience*, 8, 932.
3 doi:10.3389/fnhum.2014.00932
- 4 Alvarez, G. A., & Cavanagh, P. (2004). The capacity of visual short term memory is set both by visual
5 information load and by number of objects. *Psychological Science*, 15, 106-111. doi:10.1111/j.0963-
6 7214.2004.01502006.x
- 7 Alvarez, G. A., & Thompson, T. W. (2009). Overwriting and rebinding: Why feature-switch detection
8 tasks underestimate the binding capacity of visual working memory. *Visual Cognition*, 17, 141–159.
9 doi:10.1080/13506280802265496
- 10 Annac, E., Zang, X., Müller, H. J., & Geyer, T. (2019). A secondary task is not always costly: Context-
11 based guidance of visual search survives interference from a demanding working memory task.
12 *British Journal of Psychology*. Advance online publication. doi:10.1111/bjop.12346
- 13 Baddeley, A. (1986). *Oxford psychology series, No. 11. Working memory*. New York, NY: Clarendon
14 Press/Oxford University Press.
- 15 Bays, P. M., & Husain, M. (2008). Dynamic shifts of limited working memory resources in human vision.
16 *Science*, 321, 851-854. doi:10.1126/science.1158023
- 17 Bays, P. M., Wu, E. Y., & Husain, M. (2011). Storage and binding of object features in visual working
18 memory. *Neuropsychologia*, 49, 1622–1631. doi:10.1016/j.neuropsychologia.2010.12.023
- 19 Bae, G.-Y., & Luck, S. J. (2019). What happens to an individual visual working memory representation
20 when it is interrupted? *British Journal of Psychology*. Advance online publication.
21 doi:10.1111/bjop.12339
- 22 Berggren, N., & Eimer, M. (2019). Visual working memory load disrupts the space-based attentional
23 guidance of target selection. *British Journal of Psychology*. Advance online publication.
24 doi:10.1111/bjop.12323
- 25 Block, N. (2011). Perceptual consciousness overflows cognitive access. *Trends in Cognitive Sciences*, 15,
26 567-575. doi:10.1016/j.tics.2011.11.001

- 1 Brady, T. F., & Alvarez, G. A. (2011). Hierarchical encoding in visual working memory: Ensemble
2 statistics bias memory for individual items. *Psychological Science*, *22*, 384-392.
3 doi:10.1177/0956797610397956
- 4 Brady, T. F., & Alvarez, G. A. (2015a). Contextual effects in visual working memory reveal hierarchically
5 structured memory representations. *Journal of Vision*, *15*(15), 6. doi: 10.1167/15.15.6.
- 6 Brady, T. F., & Alvarez, G. A. (2015b). No evidence for a fixed object limit in working memory: Spatial
7 ensemble representations inflate estimates of working memory capacity for complex objects. *Journal*
8 *of Experimental Psychology: Learning, Memory, and Cognition*, *41*, 921-929.
9 doi:10.1037/xlm0000075
- 10 Brady, T. F., Störmer, V. S., & Alvarez, G. A. (2016). Working memory is not fixed-capacity: More
11 active storage capacity for real-world objects than for simple stimuli. *PNAS*, *113*, 7459–7464.
12 doi:10.1073/pnas.1520027113
- 13 Brady, T. F., & Tenenbaum, J. B. (2013). A probabilistic model of visual working memory: Incorporating
14 higher order regularities into working memory capacity estimates. *Psychological Review*, *120*, 85-
15 109. doi:10.1037/a0030779
- 16 Bundesen, C., Habekost, T., & Kyllingsbæk, S. (2005). A neural theory of visual attention: Bridging
17 cognition and neurophysiology. *Psychological Review*, *112*, 291-328. doi:10.1037/0033-
18 295X.112.2.291
- 19 Bundesen, C., Habekost, T., & Kyllingsbæk, S. (2011). A neural theory of visual attention and short-term
20 memory (NTVA). *Neuropsychologia*, *49*, 1446–1457. doi:10.1016/j.neuropsychologia.2010.12.006
- 21 Christophel, T. B., Cichy, R. M., Hebart, M. N., & Haynes, J.-D. (2015). Parietal and early visual cortices
22 encode working memory content across mental transformations. *NeuroImage*, *106*, 198–206.
23 doi:10.1016/j.neuroimage.2014.11.018
- 24 Christophel, T. B., Klink, P. C., Spitzer, B., Roelfsema, P. R., & Haynes, J.-D. (2017). The distributed
25 nature of working memory. *Trends in Cognitive Sciences*, *21*, 111–124.
26 doi:10.1016/j.tics.2016.12.007

- 1 Cowan, N. (1999). An embedded-processes model of working memory. In A. Miyake & P. Shah (Eds.),
2 *Models of Working Memory: Mechanisms of Active Maintenance and Executive Control* (pp. 62-101).
3 Cambridge: Cambridge University Press. doi:10.1017/CBO9781139174909.006
- 4 Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage
5 capacity. *Behavioral and Brain Sciences*, 24, 87-185. doi:10.1017/S0140525X01003922
- 6 Cronin, D. A., & Irwin, D. E. (2018). Visual working memory supports perceptual stability across
7 saccadic eye movements. *Journal of Experimental Psychology: Human Perception and Performance*,
8 44, 1739–1759. doi:10.1037/xhp0000567
- 9 Curby, K. M., & Gauthier, I. (2007). A visual short-term memory advantage for faces. *Psychonomic*
10 *Bulletin & Review*, 14, 620–628. doi:10.3758/BF03196811
- 11 Curby, K. M., Glazek, K., & Gauthier, I. (2009). A visual short-term memory advantage for objects of
12 expertise. *Journal of Experimental Psychology: Human Perception and Performance*, 35, 94–107.
13 doi:10.1037/0096-1523.35.1.94
- 14 Curby, Smith, Moerel, & Dyson (2019). The cost of facing fear: Visual working memory is impaired for
15 faces expressing fear. *British Journal of Psychology*. Advance online publication.
16 doi:10.1111/bjop.12324
- 17 Czoschke, S., Fischer, C., Beitner, J., Kaiser, J., & Bledowski, C. (2019). Two types of serial dependence
18 in visual working memory. *British Journal of Psychology*. Advance online publication.
19 doi:10.1111/bjop.12349
- 20 Dehaene, S., & Naccache, L. (2001). Towards a cognitive neuroscience of consciousness: Basic evidence
21 and a workspace framework. *Cognition*, 79, 1–37. doi:10.1016/S0010-0277(00)00123-2
- 22 Dodwell, G., Müller, H. J., & Töllner, T. (2019). Electroencephalographic evidence for improved visual
23 working memory performance during standing and exercise. *British Journal of Psychology*. Advance
24 online publication. doi:10.1111/bjop.12352

- 1 Drew, T., & Vogel, E. K. (2008). Neural measures of individual differences in selecting and tracking
2 multiple moving objects. *The Journal of Neuroscience*, 28, 4183–4191.
3 doi:10.1523/JNEUROSCI.0556-08.2008
- 4 Dehaene, S., & Naccache, L. (2001). Towards a cognitive neuroscience of consciousness: Basic evidence
5 and a workspace framework. *Cognition*, 79, 1–37. doi:10.1016/S0010-0277(00)00123-2
- 6 Donkin, C., Nosofsky, R. M., Gold, J. M., & Shiffrin, R. M. (2013). Discrete-slots models of visual
7 working-memory response times. *Psychological Review*, 120, 873–902. doi:10.1037/a0034247
- 8 Eimer, M. (1996). The N2pc component as an indicator of attentional selectivity. *Electroencephalography
9 & Clinical Neurophysiology*, 99, 225–234. doi:10.1016/0013-4694(96)95711-9
- 10 Fougnie, D., Asplund, C. L., & Marois, R. (2010). What are the units of storage in visual working
11 memory? *Journal of Vision*, 10(12), 27. doi:10.1167/10.12.27
- 12 Fougnie, D., Cormiea, S. M., & Alvarez, G. A. (2013). Object-based benefits without object-based
13 representations. *Journal of Experimental Psychology: General*, 142, 621–626. doi:10.1037/a0030300
- 14 Fougnie, D., Suchow, J. W., & Alvarez, G. A. (2012). Variability in the quality of visual working
15 memory. *Nature Communications*, 3, 1229. doi:10.1038/ncomms2237
- 16 Fukuda, K., Vogel, E., Mayr, U., & Awh, E. (2010). Quantity, not quality: The relationship between fluid
17 intelligence and working memory capacity. *Psychonomic Bulletin & Review*, 17, 673–679.
18 doi:10.3758/17.5.673
- 19 Gilchrist, A. L., & Cowan, N. (2014). A two-stage search of visual working memory: Investigating speed
20 in the change-detection paradigm. *Attention, Perception, & Psychophysics*, 76, 2031–2050.
21 doi:10.3758/s13414-014-0704-5
- 22 Griffin, I. C., & Nobre, A. C. (2003). Orientating attention to locations in internal representations. *Journal
23 of Cognitive Neuroscience*, 15, 1176–1194. doi:10.1162/089892903322598139
- 24 Hardman, K. O., Vergauwe, E., & Ricker, T. J. (2017). Categorical working memory representations are
25 used in delayed estimation of continuous colors. *Journal of Experimental Psychology: Human
26 Perception and Performance*, 43, 30–54. doi:10.1037/xhp0000290

- 1 Harrison, S. A., & Tong, F. (2009). Decoding reveals the contents of visual working memory in early
2 visual areas. *Nature*, *458*, 632–635. doi:10.1038/nature07832
- 3 Herman, P. A., Lundqvist, M., & Lansner, A. (2013). Nested theta to gamma oscillations and precise
4 spatiotemporal firing during memory retrieval in a simulated attractor network. *Brain Research*, *1536*,
5 68–87. doi:10.1016/j.brainres.2013.08.002
- 6 Hollingworth, A., & Hwang, S. (2013). The relationship between visual working memory and attention:
7 retention of precise colour information in the absence of effects on perceptual selection. *Philosophical*
8 *Transactions of the Royal Society of London. Series B, Biological Sciences*, *368*, 20130061.
9 doi:10.1098/rstb.2013.0061
- 10 Hyun, J., Woodman, G. F., Vogel, E. K., Hollingworth, A., & Luck, S. J. (2009). The comparison of
11 visual working memory representations with perceptual inputs. *Journal of Experimental Psychology:*
12 *Human Perception and Performance*, *35*, 1140-1160. doi:10.1037/a0015019
- 13 Jackson, M. C., Linden, D. E. J., & Raymond, J. E. (2014). Angry expressions strengthen the encoding
14 and maintenance of face identity representations in visual working memory. *Cognition and Emotion*,
15 *28*, 278–297. doi:10.1080/02699931.2013.816655
- 16 Jackson, M. C., & Raymond, J. E. (2008). Familiarity enhances visual working memory for faces. *Journal*
17 *of Experimental Psychology: Human Perception and Performance*, *34*, 556-568. doi:10.1037/0096-
18 1523.34.3.556
- 19 Jackson, M. C., Wu, C., Linden, D. J., & Raymond, J. E. (2009). Enhanced visual short-term memory for
20 angry faces. *Journal of Experimental Psychology: Human Perception and Performance*, *35*, 363-374.
21 doi:10.1037/a0013895
- 22 Kensinger, E. A., & Corkin, S. (2003). Effect of negative emotional content on working memory and
23 long-term memory. *Emotion*, *3*, 378–393. doi:10.1037/1528-3542.3.4.378
- 24 Liesefeld, A. M., Liesefeld, H. R., & Zimmer, H. D. (2014). Intercommunication between prefrontal and
25 posterior brain regions for protecting visual working memory from distractor interference.
26 *Psychological Science*, *25*, 325-333. doi:10.1177/0956797613501170

- 1 Liesefeld, H. R., Liesefeld, A. M., & Müller, H. J. (2019). Two good reasons to say ‘change!’ – ensemble
2 representations as well as item representations impact standard measures of VWM capacity. *British*
3 *Journal of Psychology*. Advance online publication. doi:10.1111/bjop.12359
- 4 Liesefeld, H. R., Liesefeld, A. M., Müller, H. J., & Rangelov, D. (2017). Saliency maps for finding
5 changes in visual scenes? *Attention, Perception, & Psychophysics*, *79*, 2190-2201.
6 doi:10.3758/s13414-017-1383-9
- 7 Liesefeld, H. R., & Zimmer, H. D. (2013). Think spatial: The representation in mental rotation is
8 nonvisual. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *39*, 167-182.
9 doi:10.1037/a0028904
- 10 Lisman, J. E., & Idiart, M. A. P. (1995). Storage of 7 ± 2 short-term memories in oscillatory subcycles.
11 *Science*, *267*, 1512–1515. doi:10.1126/science.7878473
- 12 Lisman, J. E., & Jensen, O. (2013). The θ - γ neural code. *Neuron*, *77*, 1002–1016.
13 doi:10.1016/j.neuron.2013.03.007
- 14 Logie, R. H. (1995). *Visuo-spatial working memory*. London, UK: Psychology Press.
- 15 Luck, S. J., & Hillyard, S. A. (1994a). Electrophysiological correlates of feature analysis during visual
16 search. *Psychophysiology*, *31*, 291–308. doi: 10.1111/j.1469-8986.1994.tb02218.x
- 17 Luck, S. J., & Hillyard, S. A. (1994b). Spatial filtering during visual search: Evidence from human
18 electrophysiology. *Journal of Experimental Psychology: Human Perception and Performance*, *20*,
19 1000–1014. doi: 10.1037/0096-1523.20.5.1000
- 20 Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions.
21 *Nature*, *390*, 279-281. doi:10.1038/36846
- 22 Luck, S. J., & Vogel, E. K. (2013). Visual working memory capacity: From psychophysics and
23 neurobiology to individual differences. *Trends in Cognitive Sciences*, *17*, 391-400.
24 doi:10.1016/j.tics.2013.06.006

- 1 Luria, R., Balaban, H., Awh, E., & Vogel, E. K. (2016). The contralateral delay activity as a neural
2 measure of visual working memory. *Neuroscience and Biobehavioral Reviews*, *62*, 100–108.
3 doi:10.1016/j.neubiorev.2016.01.003
- 4 Ma, W. J. (2019). Problematic usage of the Zhang and Luck mixture model. *bioRxiv*. Preprint.
5 doi:10.1101/268961
- 6 Maran, T., Sachse, P., & Furtner, M. (2015). From specificity to sensitivity: Affective states modulate
7 visual working memory for emotional expressive faces. *Frontiers in Psychology*, *6*, 1297. doi:
8 10.3389/fpsyg.2015.01297
- 9 Mather, M. (2007). Emotional arousal and memory binding: An object-based framework. *Perspectives in*
10 *Psychological Science*, *2*, 33-52. doi:10.1111/j.1745-6916.2007.00028.x
- 11 Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for
12 processing information. *Psychological Review*, *63*, 81–97. doi:10.1037/h0043158
- 13 Morey, C. C. (2019). Perceptual grouping boosts visual working memory capacity and reduces effort
14 during retention. *British Journal of Psychology*. Advance online publication. doi:10.1111/bjop.12355
- 15 Morey, C. C., Cong, Y., Zheng, Y., Price, M., & Morey, R. D. (2015). The color-sharing bonus: Roles of
16 perceptual organization and attentive processes in visual working memory. *Archives of Scientific*
17 *Psychology*, *3*, 18–29. doi:10.1037/arc0000014
- 18 Oberauer, K. (2002). Access to information in working memory: Exploring the focus of attention. *Journal*
19 *of Experimental Psychology: Learning, Memory, and Cognition*, *28*, 411–421. doi:10.1037/0278-
20 7393.28.3.411
- 21 Oberauer, K. (2009). Design for a working memory. *Psychology of Learning and Motivation*, *51*, 45–100.
22 doi: 10.1016/S0079-7421(09)51002-X
- 23 Oberauer, K., Lewandowsky, S., Farrell, S., Jarrold, C., & Greaves, M. (2012). Modeling working
24 memory: An interference model of complex span. *Psychonomic Bulletin & Review*, *19*, 779–819.
25 doi:10.3758/s13423-012-0272-4

- 1 Oberauer, K., & Lin, H. (2017). An interference model of visual working memory. *Psychological Review*,
2 124, 21-59. doi:10.1037/rev000004
- 3 Olivers, C. L., Peters, J., Houtkamp, R., & Roelfsema, P. R. (2011). Different states in visual working
4 memory: When it guides attention and when it does not. *Trends in Cognitive Sciences*, 15, 327-334.
5 doi:10.1016/j.tics.2011.05.004
- 6 Olson, I. R., & Jiang, Y. (2002). Is visual short-term memory object based? Rejection of the “strong-
7 object” hypothesis. *Perception & Psychophysics*, 64, 1055–1067. doi:10.3758/BF03194756
- 8 Park, H.-B., Zhang, W., & Hyun, J.-S. (2017). Dissociating models of visual working memory by
9 reaction-time distribution analysis. *Acta Psychologica*, 173, 21–31. doi:10.1016/j.actpsy.2016.12.003
- 10 Pashler, H. (1988). Familiarity and visual change detection. *Perception & Psychophysics*, 44, 369-378.
11 doi:10.3758/BF03210419
- 12 Peterson, D. J., & Berryhill, M. E. (2013). The Gestalt principle of similarity benefits visual working
13 memory. *Psychonomic Bulletin & Review*, 20, 1282–1289. doi:10.3758/s13423-013-0460-x
- 14 Pollmann, S. (2019). Working memory dependence of spatial contextual cueing for visual search. *British*
15 *Journal of Psychology*. Advance online publication. doi:10.1111/bjop.12311
- 16 Quinlan, P. T., & Cohen, D. J. (2012). Grouping and binding in visual short-term memory. *Journal of*
17 *Experimental Psychology: Learning, Memory, and Cognition*, 38, 1432–1438. doi:10.1037/a0027866
- 18 Reinhart, R. M. G., McClenahan, L. J., & Woodman, G. F. (2016). Attention’s accelerator. *Psychological*
19 *Science*, 27, 790–798. doi:10.1177/0956797616636416
- 20 Rhodes, S., & Cowan, N. (2019). *British Journal of Psychology*.
- 21 Rouder, J. N., Morey, R. D., Morey, C. C., & Cowan, N. (2011). How to measure working memory
22 capacity in the change detection paradigm. *Psychonomic Bulletin & Review*, 18, 324-330.
23 doi:10.3758/s13423-011-0055-3
- 24 Sauseng, P., Klimesch, W., Heise, K. F., Gruber, W. R., Holz, E., Karim, A. A., ... Hummel, F. C. (2009).
25 Brain oscillatory substrates of visual short-term memory capacity. *Current Biology*, 19, 1846–1852.
26 doi:10.1016/j.cub.2009.08.062

- 1 Sauseng, P., Peylo, C., Biel, A. L., Friedrich, E. V. C., & Romberg-Taylor, C. (2009). Does cross-
2 frequency phase coupling of oscillatory brain activity contribute to a better understanding of visual
3 working memory? *British Journal of Psychology*. Advance online publication.
4 doi:10.1111/bjop.12340
- 5 Schneegans, S., & Bays, P. M. (2017). Neural architecture for feature binding in visual working memory.
6 *The Journal of Neuroscience*, 37, 3913–3925. doi:10.1523/JNEUROSCI.3493-16.2017
- 7 Schneegans, S., & Bays, P. M. (2019). New perspectives on binding in visual working memory. *British*
8 *Journal of Psychology*. Advance online publication. doi:10.1111/bjop.12345
- 9 Schneider, W. X. (2013). Selective visual processing across competition episodes: a theory of task-driven
10 visual attention and working memory. *Philosophical Transactions of the Royal Society of London.*
11 *Series B, Biological Sciences*, 368, 20130060. doi:10.1098/rstb.2013.0060
- 12 Schurgin, M. W., Cunningham, C. A., Egeth, H. E., & Brady, T. F. (2018) Visual long-term memory can
13 replace active maintenance in visual working memory. bioRxiv. Preprint. doi:10.1101/381848
- 14 Serences, J. T., Ester, E. F., Vogel, E. K., & Awh, E. (2009). Stimulus-specific delay activity in human
15 primary visual cortex. *Psychological Science*, 20, 207–214. doi:10.1111/j.1467-9280.2009.02276.x
- 16 Sessa, P., Luria, R., Gotler, A., Jolicœur, P., & Dell'Acqua, R. (2011). Interhemispheric ERP asymmetries
17 over inferior parietal cortex reveal differential visual working memory maintenance for fearful versus
18 neutral facial identities. *Psychophysiology*, 48, 187–197. doi:10.1111/j.1469-8986.2010.01046.x
- 19 Soto, D., & Silvanto, J. (2016). Is conscious awareness needed for all working memory processes?
20 *Neuroscience of Consciousness*, 2016, niw009. doi:10.1093/nc/niw009
- 21 Souza, A. S., & Oberauer, K. (2016). In search of the focus of attention in working memory: 13 years of
22 the retro-cue effect. *Attention, Perception, & Psychophysics*, 78, 1839–1860. doi:10.3758/s13414-
23 016-1108-5
- 24 Souza, A. S., Rerko, L., & Oberauer, K. (2016). Getting more from visual working memory: Retro-cues
25 enhance retrieval and protect from visual interference. *Journal of Experimental Psychology: Human*
26 *Perception and Performance*, 42, 890–910. doi:10.1037/xhp0000192

- 1 Sprague, T. C., Ester, E. F., & Serences, J. T. (2014). Reconstructions of information in visual spatial
2 working memory degrade with memory load. *Current Biology*, *24*, 2174–2180.
3 doi:10.1016/j.cub.2014.07.066
- 4 Swan, G., & Wyble, B. (2014). The binding pool: A model of shared neural resources for distinct items in
5 visual working memory. *Attention, Perception, & Psychophysics*, *76*, 2136–2157.
6 doi:10.3758/s13414-014-0633-3
- 7 Tabi, Y. A., Husain, M., & Manohar, S. G. (2019). Recall cues interfere with retrieval from visuospatial
8 working memory. *British Journal of Psychology*. Advance online publication.
9 doi:10.1111/bjop.12374
- 10 Todd, J. J., & Marois, R. (2004). Capacity limit of visual short-term memory in human posterior parietal
11 cortex. *Nature*, *428*, 751–754. doi:10.1038/nature02466
- 12 Treisman, A. (1996). The binding problem. *Current Opinion in Neurobiology*, *6*, 171–178.
13 doi:10.1016/S0959-4388(96)80070-5
- 14 Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*,
15 *12*, 97–136. doi:10.1016/0010-0285(80)90005-5
- 16 Tsubomi, H., Fukuda, K., Watanabe, K., & Vogel, E. K. (2013). Neural limits to representing objects still
17 within view. *The Journal of Neuroscience*, *33*, 8257–8263. doi:10.1523/JNEUROSCI.5348-12.2013
- 18 Usher, M., Bronfman, Z. Z., Talmor, S., Jacobson, H., & Eitam, B. (2018). Consciousness without report:
19 insights from summary statistics and inattention “blindness.” *Philosophical Transactions of the Royal*
20 *Society of London. Series B, Biological Sciences*, *373*. doi:10.1098/rstb.2017.0354
- 21 Unsworth, N., Fukuda, K., Awh, E., & Vogel, E. K. (2014). Working memory and fluid intelligence:
22 Capacity, attention control, and secondary memory retrieval. *Cognitive Psychology*, *71*, 1–26.
23 doi:10.1016/j.cogpsych.2014.01.003
- 24 van den Berg, R., Awh, E., & Ma, W. J. (2014). Factorial comparison of working memory models.
25 *Psychological Review*, *121*, 124–149. doi:10.1037/a0035234

- 1 van den Berg, R., Shin, H., Chou, W., George, R., & Ma, W. J. (2012). Variability in encoding precision
2 accounts for visual short-term memory limitations. *PNAS*, *109*, 8780-8785.
3 doi:10.1073/pnas.1117465109
- 4 Van Vugt, M. K., Chakravarthi, R., & Lachaux, J.-P. (2014). For whom the bell tolls: Periodic reactivation
5 of sensory cortex in the gamma band as a substrate of visual working memory maintenance. *Frontiers*
6 *in Human Neuroscience*, *8*, 696. doi:10.3389/fnhum.2014.00696
- 7 Vogel, E. K., & Machizawa, M. G. (2004). Neural activity predicts individual differences in visual
8 working memory capacity. *Nature*, *428*, 748-751. doi:10.1038/nature02447
- 9 Vogel, E. K., McCullough, A. W., & Machizawa, M. G. (2005). Neural measures reveal individual
10 differences in controlling access to working memory. *Nature*, *438*, 500-503. doi:10.1038/nature04171
- 11 Vosskuhl, J., Huster, R. J., & Herrmann, C. S. (2015). Increase in short-term memory capacity induced by
12 down-regulating individual theta frequency via transcranial alternating current stimulation. *Frontiers*
13 *in Human Neuroscience*, *9*, 257. doi:10.3389/fnhum.2015.00257
- 14 Wheeler, M. E., & Treisman, A. M. (2002). Binding in short-term visual memory. *Journal of*
15 *Experimental Psychology: General*, *131*, 48-64. doi:10.1037/0096-3445.131.1.48
- 16 Wilken, P., & Ma, W. J. (2004). A detection theory account of change detection. *Journal of Vision*, *4*,
17 1120–1135. doi:10.1167/4.12.11
- 18 Wolinski, N., Cooper, N. R., Sauseng, P., & Romei, V. (2018). The speed of parietal theta frequency
19 drives visuospatial working memory capacity. *PLoS Biology*, *16*, e2005348.
20 doi:10.1371/journal.pbio.2005348
- 21 Xu, Y. (2002). Encoding color and shape from different parts of an object in visual short-term memory.
22 *Perception & Psychophysics*, *64*, 1260–1280. doi:10.3758/BF03194770
- 23 Xu, Y., & Chun, M. M. (2006). Dissociable neural mechanisms supporting visual short-term memory for
24 objects. *Nature*, *440*, 91-95. doi:10.1038/nature04262
- 25 Zhang, W., & Luck, S. J. (2008). Discrete fixed-resolution representations in visual working memory.
26 *Nature*, *453*, 233-235. doi:10.1038/nature06860

- 1 Zimmer, H. D. (2008). Visual and spatial working memory: From boxes to networks. *Neuroscience and*
- 2 *Biobehavioral Reviews*, 32, 1373–1395. doi:10.1016/j.neubiorev.2008.05.016
- 3 Zimmer, H. D., & Liesefeld, H. R. (2011). Spatial information in visual working memory. In A.
- 4 Vandierendonck & A. Szmalec (Eds.), *Spatial working memory* (pp. 46-66). Hove, England:
- 5 Psychology Press.
- 6