British Journal of Psychology (2019), 110, 449–460

The British Psychological Society

www.wileyonlinelibrary.com

Commentary

Flexible representations in visual working memory and interactions with long-term learning: Commentary on the special issue

Stephen Rhodes* and Nelson Cowan*

Department of Psychological Sciences, University of Missouri, Columbia, Missouri, USA

This special issue of the *British Journal of Psychology* brings together cutting edge research on a range of topics in visual working memory (VWM). In this commentary, we attempt to summarize common themes in current VWM research exemplified in this issue. The articles include several reviews of important topics as well as empirical papers covering three main themes. The first concerns the nature of mental representations of memoranda in the commonly used delayed estimation task, where both fine-grained and broad categorical details appear to be represented, and their susceptibility to interference. The second concerns interactions between VWM representations, both those that produce individuation of representations and those that create an overarching ensemble structure. Finally, the third main topic concerns the use of VWM during visual search and in the learning of repeated configurations in search displays. The work presented here, and other work in the field, points to a rich interplay between representations in VWM but also between VWM and information in long-term memory. Opportunities for further investigation are highlighted throughout.

The past 20–30 years have seen a surge of interest in visual working memory (VWM), and it has become a lively field with many, often overlapping, topics of investigation (and debate) concerning: whether VWM is limited by the number of items that can be held (Adam, Vogel, & Awh, 2017; Cowan, 2001; Luck & Vogel, 1997) or by the distribution of a flexible resource (Bays, Catalao, & Husain, 2009; van den Berg, Shin, Chou, George, & Ma, 2012); whether representation in VWM is object-based and how features are retained bound in VWM (see Schneegans & Bays, this issue, for a review); how structure and redundancy in to-be-remembered material influences performance (Brady & Alvarez, 2011; Liesefeld, Liesefeld, & Müller, this issue; Morey, this issue); to what extent storage of visual material occurs separately from storage of other material (Berggren & Eimer, this issue; Logie, 1995; Morey, 2018); what role VWM plays in real-world looking behaviour and visual search (Annac, Zang, Müller, & Geyer, this issue; Berggren & Eimer, this issue; Pollmann, this issue); and questions about the neurobiology underlying VWM

*Correspondence should be addressed to Stephen Rhodes, Rotman Research Institute, Baycrest, 3560 Bathurst St, Toronto, ON M6A 2E1, Canada (email: srhodes@research.baycrest.org).
and
Nelson Cowan, Department of Psychological Sciences, University of Missouri, 210 McAlester Hall, Columbia MO 65211, USA (email: cowann@missouri.edu).

DOI:10.1111/bjop.12380

(for a review of oscillatory underpinnings, see Sauseng, Peylo, Biel, Friedrich, & Romberg-Taylor, this issue) and what factors influence its capacity, such as the emotional valence of items (Curby, Smith, Moerel, & Dyson, this issue) or exercise (Dodwell, Müller, & Töllner, this issue).

The above is a non-exhaustive list, and not even a full issue of a journal could attempt to address all of these issues (for other topics see, e.g., Suchow, Fougnie, Brady, & Alvarez, 2014, and the summary section of this article). Indeed, as evidence of a thriving area of research, this special issue of the *British Journal of Psychology* has brought together work addressing a range of questions regarding VWM. In reading through these articles, we picked up three broad themes, around which we arrange our commentary. The first concerns the nature of VWM representations, particularly those utilized in delayed estimation tasks, and the effects of interference on these representations (Bae & Luck, this issue; Tabi, Husain, & Manohar, this issue). The second topic concerns interactions between representations in VWM, owing to overarching structure in the to-be-remembered material or to previously relevant information (Czoschke, Fischer, Beitner, Kaiser, & Bledowski, this issue; Liesefeld *et al.*, this issue; Morey, this issue). The third broad topic concerns the involvement of VWM in visual search (Berggren & Eimer, this issue) and in the longer-term learning of repeated material in visual search tasks (Annac *et al.*, this issue; Pollmann, this issue). Throughout, we aim to point to avenues for further work, and at the end, we attempt to summarize what these findings tell us about VWM.

The nature of VWM representations and their susceptibility to interference

Initial work with the delayed estimation paradigm assumed that, across the circular space that stimuli are typically sampled from, each possible stimulus value is treated equally in VWM. This is exemplified in the practice of focusing modelling efforts on the histogram of errors (i.e., deviations from the target stimulus). However, plotting of the responded feature value as a function of the presented value has revealed strong categorical biases in VWM representations (Rouder, Thiele, Province, Cusumano, & Cowan, 2014). For example, particular colours are over-represented in participant responses (Bae, Olkkonen, Allred, & Flombaum, 2015; Hardman, Vergauwe, & Ricker, 2017) or responses appear to be biased away from cardinal (i.e., north, south, east, west) orientations (Pratte, Park, Rademaker, & Tong, 2017).

Research has begun to examine the factors that determine whether delayed estimation reports reflect continuous or categorical information in VWM (Donkin, Nosofsky, Gold, & Shiffrin, 2015; Hardman *et al.*, 2017; Ricker & Hardman, 2017), and the study of Bae and Luck (this issue) provides an insight into potential factors. They examine the effect of a simple distracting task, performed during the retention interval, on the representation of a single orientation in VWM. Importantly, they included trials where participants expected the secondary task, which was either a visual letter (Experiment 1) or tone discrimination task (Experiment 2), but it did not appear, in addition to baseline trials where participants did not expect a secondary task. This allowed them to distinguish the effect of preparation to perform a secondary task from having to actually perform the task during the retention interval. When participants had to make a response to the visual letter task, both the precision of the orientation memory response decreased and the degree of categorical bias, away from cardinal orientations, increased (see also Hardman *et al.*, 2017). This was not the case for orientation memory during a tone discrimination task. However, for both secondary tasks, there was a tendency towards more categorically biased estimation of orientation when participants expected to have to respond to the task, whether or not it was actually presented.

These findings, and the authors' discussion of them, were of particular interest to us given our recent interest in the idea of offloading information from the focus of attention (FoA) to attention-free modes of maintenance (e.g., activated long-term memory; Rhodes & Cowan, 2018). Bae and Luck (this issue) propose that the FoA may serve to maintain precise metric information while other forms of maintenance can only support coarse categorical information. They propose that encoding the letter (but not the tone) into VWM displaces the orientation stimulus from the focus, producing more categorical responding, and that participants may do some pre-emptive offloading to prepare for secondary tasks regardless of the material. These findings also appear to be in line with those of Hardman *et al.* (2017, Experiment 2) who presented participants with sequences of four colours and varied the number of tone discrimination responses required during the maintenance interval. While Hardman *et al.* (2017) found that the increase in cognitive load only affected the probability that items were recalled from memory and had no effect on the probability of categorical recall, they also found that overall categorical storage was higher in the experiment with a secondary tone task relative to their first experiment which had no tone task. This seems consistent with the notion of offloading and goes some way to show the generality of the effect (across orientation and colour memory items). It would be interesting to see whether a cognitive load effect would be obtained with a visual secondary task, as greater similarity between items increases the need for control processes (Gosseries *et al.*, 2018) that may conflict with concurrent processing.

In addition to interfering effects from concurrent tasks, it is highly likely that the way in which memory is probed can have distorting effects on performance. Indeed, memory for the exact combination of features (e.g., colour and shape) has repeatedly been shown to be susceptible to interference and overwriting by information presented at test (Alvarez & Thompson, 2009; Logie, Brockmole, & Vandenbroucke, 2009; for a review, see Schneegans & Bays, this issue). In delayed estimation tasks, it is often the case that the memory probe is started at some random value that the participant must adjust to the remembered value. For example, a probe arrow may be presented at a particular orientation and participants use the mouse to adjust the angle. Comparing this mode of probing memory to one where a starting value is not presented, Tabi *et al.* (this issue) find that the former leads to less precise recall (see also, Souza, Rerko, & Oberauer, 2016). Interestingly, the amount of interference imposed by the probe did not depend on the similarity of the probe's starting angle relative to the target item. This is in line with the notion that features of the display at test, such as the starting value, get integrated with the contents of memory and possibly averaged producing a less pure representation (Anderson, 1981). However, focusing attention on a particular item prior to the onset of the probe display appears to protect VWM from such interference (Souza *et al.*, 2016). It is also interesting to note that Tabi *et al.* (this issue) analyse their data with the mixture model of Bays *et al.* (2009) but, given the findings above, it would be interesting to also apply the approach of Hardman *et al.* (2017) to examine potential changes in the nature of the representations available with different testing procedures.

Interactions between representations in VWM

Recent work has shown that the amount of information that can be retained in VWM is greatly boosted by structural regularities or redundancy in memory arrays (Brady &

Alvarez, 2011; Brady, Konkle, & Alvarez, 2009; Morey, Cong, Zheng, Price, & Morey, 2015). For example, when pairs of colours are repeated in close spatial proximity across the course of a VWM experiment, observers show performance increases consistent with compression of the information (Brady & Tenenbaum, 2013). Work in this special issue sheds light both on how these regularities might be extracted and how they may influence performance on more standard VWM tasks.

Morey (this issue) shows that including from 1 to 3 duplicated colours in a memory array increasingly benefits estimated VWM capacity for non-repeated items in the display, suggesting freeing up of capacity via redundancy. Interestingly, measurements of pupil dilation, at least in younger participants, suggested that this redundancy reduces the effort required to maintain the memory array across the delay interval. Morey also observes that the repeated items are quickly fixated during the study period, suggesting that the structure of visual information is rapidly extracted, freeing up attention to maintain information that less easily fits into the extracted structure (in this case, non-repeated colours).

Once structural information is extracted, it has been shown to affect performance on a number of VWM tasks (e.g. Brady & Alvarez, 2011). However, these tasks tend to have introduced regularity into the studied material in order to study its effects (e.g., the repetition of colours used above). Does structural information influence more standard VWM tasks, such as change detection, where stimuli are typically chosen to be as distinct as possible? Liesefeld *et al.* (this issue) used a whole-display change detection task in which categorically distinct colours are simultaneously presented at study and, at test, participants must respond ‘change’ when a single item changes colour. To assess whether structural, or ensemble, representations play a role in this more standard VWM task, they followed up the initial ‘change’ or ‘no-change’ response with an additional requirement to localize the altered item when a change had occurred. Applying Pashler’s (1988) method of determining the number of items in memory, and the true rate of change detection, the authors find that participants correctly localize the change after asserting that one had occurred on substantially fewer trials than would be predicted (assuming that true ‘change’ responses always confer information about the location of the change, a point to which we return below). In addition, they find that when the change is incorrectly localized the selected item tends to be closer to the actually changed item than would be predicted by chance. To fit their data, the authors propose a modification of the Pashler formula for calculating the number of items in VWM that takes into account the influence of ensemble representations. Although ensemble representations are indeed important and have been shown to influence behaviour in a range of paradigms (see Brady & Alvarez, 2011; Brady & Tenenbaum, 2013; Brady *et al.*, 2009), we believe that their influence in this task is more difficult to establish, and we find that more work in this area is a priority, as we outline below.

Recently, we (Rhodes, Cowan, Hardman, & Logie, 2018; Rouder, Morey, Morey, & Cowan, 2011) have also proposed an alteration to the Pashler model in which people use knowledge of the number of items they have in memory to inform their guessing behaviour. This account does not include ensemble representations but does allow participants to exhibit ‘informed guessing’ in whole-display change detection much like the model Liesefeld *et al.* (this issue) present. Our account would need to be modified to produce predictions for localization responses, which as Liesefeld *et al.* (this issue) describe can also be informed (i.e., even if the participant does not know the changed item, they can use the items in memory to rule out particular locations). However, we note that there is nothing in the original Pashler model of whole-display change detection that *necessitates* that the observer retains the correct binding of colour and location to produce a change detection response. Rather, the observer is assumed to match each of the items in memory with the colours in the probe display (see Rouder *et al.*, 2011). This can occur irrespective of remembered location. If one of the items in memory is absent from the probe set, a 'change' response is given; otherwise, if the array exceeds capacity, a guess must be made. Note that, following the logic of the Pashler model, for large set sizes that exceed capacity it is not sufficient for the observer to merely look for mismatches between items in memory and items in the test array, as this will always be the case given that a subset of the items were not retained. The idea that change detection can proceed without access to the initially encoded locations is supported by studies showing well above chance performance when the layout of colours is scrambled between the study and test displays (Jiang, Olson, & Chun, 2000; Woodman, Vogel, & Luck, 2012).

Given that this change response can occur without having the correct colour-location binding in VWM, it is not clear to us that the subsequent localization performance observed by Liesefeld *et al.* (this issue) is in fact lower than would be predicted by standard item models of change detection. Thus, it seems likely that a standard item model could account for these findings with the assumption that on a proportion of trials where the change is detected the location of the changed item is lost or inaccurate. Indeed, noisy representation of the conjunction of colour and location can produce erroneous bindings and would contribute to such trials (for a review, see Schneegans & Bays, this issue).[1] Nevertheless, the conventional item account of change detection may struggle to account for the finding that people tend to err close to the location of the changed item (although the items in memory would constrain the possible changed locations). One potential follow-up that may help disambiguate the ensemble-based and more standard item-based models of change detection would be to adopt the method of Liesefeld *et al.* (this issue), in asking for both change detection and localization responses, but to scramble the locations of the colours between study and test (Jiang *et al.*, 2000; Woodman *et al.*, 2012). This would remove any ambiguity as to whether location is used in the change detection comparison process, as location would now be rendered uninformative, and would allow for clearer diverging predictions from the item and ensemble accounts. In any case, the findings of Liesefeld *et al.* (this issue) (and those of Tabi *et al.*, this issue) clearly demonstrate the importance of carefully considering the way in which VWM is probed; there may be subtle influences that bias estimates of the capacity or precision of VWM.

As previously noted, structural relations between items in VWM task displays can influence task performance, but interactions between VWM representations are not limited to the effects of structure. Recent work has begun to examine sequential dependencies between representations in VWM. Some studies have found attraction, such that responses to a particular item demonstrate a bias towards the item from the previous trial. This attraction is particularly strong when the two items are similar, for example, similar angles of orientation (Fischer & Whitney, 2014) or close spatial locations (Bliss, Sun, & D'Esposito, 2017), and drops off with greater distance between the current and previous stimulus. On the other hand, some have reported that similar items actually

[1] *We note that Liesefeld* et al. *(this issue) considered an extension of the standard item model in which location swaps between items in memory could trigger 'change' responses without necessarily accurate localization. However, it is unclear to us why a swap of the location of colours in memory would produce a 'change' response in a task where the aim is to identify the introduction of a brand new colour. Nevertheless, further developments of such a swapping account may be useful.*

repel each other, particularly when both need to be held in VWM on the same trial (Bae & Luck, 2017).

Using these diverging findings as a starting point, Czoschke *et al.* (this issue) demonstrate both repulsion *and* attraction in the same paradigm. Specifically, they find that recall of one of a pair of motion stimuli (random dot patterns moving in a coherent direction) within a trial tends to be repelled from the other, such that responses to the second item are 'pushed away' from the first. Simultaneously, stimuli across distinct trials tend to attract one another, in that responses to the item on trial n are 'pulled' towards the second item presented on trial $n - 1$. This latter finding appears to be dependent on the previous item having been cued for report on the previous trial, and thus possibly still being present in the FoA. These two types of dependence, operating simultaneously, suggest that representations are individuated to avoid confusion within a trial but that VWM can still take advantage of prior selected information to support currently relevant representations. Given that these attraction and repulsion effects have been found individually with a range of stimuli, a clear question is to what extent both being present in the same task is a general phenomenon. Further, if cued items from previous trials do still reside in the FoA, to cause attraction on the subsequent trial, then it may be possible to remove such attractive effects by interspersing some demanding secondary task.

The involvement of VWM in visual search and long-term learning

Several papers in the issue deal with the role of VWM in visual search. In visual search tasks, participants have to keep track of the target features in order to correctly identify them in the search display. An unresolved question is whether these features, or 'attentional templates', are retained in VWM, especially when they remain constant for a series of trials, where they could be offloaded to other forms of storage long-term memory (LTM). Berggren and Eimer (this issue) present electrophysiological evidence that VWM is required to some degree to facilitate the use of these attentional templates. They had participants study one or four shapes to prepare for a single-probe change detection task. However, on two out of three trials they would instead present a search display where participants had to identify a target feature defined by spatial location. They found that the N2pc, an EEG index of match between attentional templates and features in the search display, was delayed by about 100 ms in the four shape memory load condition relative to only one shape. The authors interpret this as evidence that the search relevant locations are held in VWM even when they do not change across trials.

However, it seems to us that an alternative interpretation could be that the templates are present in activated LTM and the slowing may relate to the need to switch the FoA from the memory items to the templates, which then guide search. This suggestion gains some support from Reinhart and Woodman (2013) who found that the P170 component, an EEG index of representation in LTM, elicited to the search target increased with repeated search trials for that target. Simultaneously, the contralateral delay activity (CDA), an index of maintenance in VWM, decreased with repetition of a particular search target. Crucially, when greater monetary reward was offered on a particular trial the CDA elicited by the search target increased, consistent with loading of the learned target from long-term storage back into working memory. Reinhart and Woodman (2013) also observed that the amplitude of the N2pc component was enhanced for high-value trials but did not report any differences in latency. This is perhaps due to the fact that participants expected search on every trial in their experiments, whereas the delay in N2pc latency observed by

Berggren and Eimer (this issue) could relate to the loading of the template back into VWM from LTM when the participant realizes that search is required. These issues remain to be tested in future work. In any case, these results clearly show that a visual memory load competes with spatial attentional templates, which, as the authors note, is inconsistent with separate stores for visual and spatial information.

When the location of the target and distractors in a visual search array is repeated every other trial, reaction times become much quicker to the repeated displays over the course of the experiment compared to reaction times to novel displays. This is known as 'contextual cueing', as the (implicitly) learned context facilitates search by cueing the location of the target. Pollmann (this issue) reviews the literature on contextual cueing showing that concurrent VWM load, specifically with spatial materials, prevents the expression of speeded visual search with repetition. But when the concurrent demand is lifted, contextual cueing effects quickly manifest themselves. This points to the idea that learning the repeated search arrays can proceed even in the face of a load on VWM, but that VWM is needed to utilize this learning in what is termed 'memory guided search'. Pollmann (this issue) also discusses the potential implications of this for understanding the reduced contextual cueing effects observed in older adults with macular degeneration. The looking behaviours that these individuals use to compensate for vision loss may tax VWM, thereby preventing the expression of cueing effects, providing an interesting avenue for intervention.

In their article, also on contextual cueing, Annac *et al.* (this issue) suggest, similar to Pollmann (this issue), that VWM may act to match the acquired context representation to regions of the display during search. This matching is hampered when VWM is tied up with a spatial memory load. However, as they demonstrate, it is possible that this process of matching can be automatized over a number of trials. Typically contextual cueing effects are studied by comparing the speed of responses to repeated search displays to the speed of responses to unrepeated displays over several hundreds of trials, allowing for multiple repetitions of a subset of the displays. Annac *et al.* (this issue) wanted to see whether contextual cueing effects would appear despite a concurrent VWM load if the number of trials (and hence repetitions) were increased. They presented 720 search trials (in blocks of 24) where participants performed search along with a concurrent spatial VWM load, with 12 repeated search displays mixed in with novel ones. Looking at the first 360 trials, contextual cueing was reduced with the concurrent VWM task relative to when there was no concurrent task. However, these cueing effects were present during the later trials up to number 720 and the magnitude of the cueing effect did not differ from that observed where search was the only task. Annac *et al.* (this issue) propose that the automatized search process may actually be more efficient than that mediated by VWM. To examine this, they mixed dual- and single-task search blocks and find larger cueing effects in dual-task blocks, particularly later in the course of the experiment, in line with the suggestion that this automatized search for well-learned displays is more efficient than search relying on VWM. Interestingly, despite the speeding up of reaction times for repeated search displays, participants exhibit essentially no memory (i.e., chance performance) for the repeated displays in a subsequent recognition task, where participants had to distinguish the layout of the repeated displays from non-repeated lures.

The slow build-up of contextual cueing effects and absence of explicit memory for repeatedly viewed arrays is interesting to us in relation to other work on learning in VWM tasks. Logie and colleagues (Logie *et al.*, 2009; Shimi & Logie, 2018) have found that change detection performance for combinations of colour, shape, and location shows little improvement with repeated displays even when the same objects are presented at study on every trial. However, despite non-existent or small benefits to change detection performance, Olson and Jiang (2004) found that participants were still able to distinguish repeated from non-repeated arrays in a subsequent forced-choice recognition test at the end of the experiment. Further, learning effects are readily observed in VWM tasks when the task requires recall of the repeated features or conjunctions (Brady *et al.*, 2009; Couture & Tremblay, 2006; Logie *et al.*, 2009; Shimi & Logie, 2018). The slow learning effects for change detection paradigms are puzzling to us and we have not reached a satisfactory account of these findings, but we note several things to consider: One thing is that learning of repeated displays might be a double-edged sword for recognition paradigms, such as change detection. Detection of intact probes may increase, but, simultaneously, familiarity with the majority of items in the array may lead to erroneous no-change responses when one or a small subset of the items in the array has changed at test. Thus, we would expect increases in both the hit *and* false alarm rates (although not necessarily at the same pace) with learning, which could slow or mask improvement in a measure that aggregates over these measures (such as proportion correct or d'). Further, there are clear psychometric issues in comparing learning rates across tasks with different chance levels of performance that appear to have been left unaddressed. Finally, VWM repetition effects in recall and recognition have only been studied in separate samples of participants and it is possible that the expectation of a particular task has an influence on the kind of encoding processes engaged and, as a consequence, the observed learning rate. Thus, there are many open questions in this area. It would also be interesting to link this literature with the learning effects in visual search tasks studied by Annac *et al.* (this issue), as there appear to be both similarities (facilitation over a large number of trials) and differences (in explicit memory at the end of the experiment; e.g., Olson & Jiang, 2004).

Summary

We have discussed what we see as the three major themes in this special issue. These were as follows: (1) the nature of VWM representations, in particular those used in delayed estimation paradigms, and their susceptibility to interference from testing or concurrent tasks, (2) interactions between VWM representations, and (3) the involvement of VWM in visual search and long-term learning. The findings presented here, combined with the literature more broadly, point towards the following summary of VWM. Representation in VWM is very flexible. Perception and working memory are able to capitalize on structure and redundancy in to-be-remembered material very rapidly, allowing it to store more information more efficiently and with less effort (Morey, this issue). This is potentially useful for particular tasks, for example, whole-display change detection where knowledge about the array as a whole can benefit detection of a single change (Liesefeld *et al.*, this issue). Nevertheless, when the task demands it, working memory demonstrates the useful ability to individuate representations and keep them distinct from each other, especially when they are similar (Czoschke *et al.*, this issue). Simultaneously, VWM appears to be able to use previously relevant representations to stabilize currently relevant information by integrating similar items across trials. Establishing the generality of these two types of sequential dependence and accounting for them in models of delayed estimation will be an important task (see Bliss *et al.*, 2017).

Despite this great flexibility in dealing with different representations, VWM shows vulnerability to external interference (Bae & Luck, this issue; Tabi *et al.*, this issue). In addition, there is the often discussed capacity limit which has increasingly become a source of debate in the past decade (see Suchow *et al.*, 2014). Models in which no limit to the number of items in WM have been fairly successful in accounting for a range of findings that are seen as strong evidence for an item limit (e.g. van den Berg *et al.*, 2012). Nevertheless, some recent strong evidence of guessing responses in delayed estimation tasks is difficult to reconcile with a strict resource position and does point to a substantial proportion of trials at larger set sizes where the observer is in a state of having no information about a subset of the items (Adam *et al.*, 2017; Rouder *et al.*, 2014).

Notwithstanding these limitations, VWM supports our ability to search the environment for relevant information (Berggren & Eimer, this issue; Reinhart & Woodman, 2013). Further, VWM supports memory guided search during the course of learning repeated search displays (Pollmann, this issue), although (possibly owing to its limited capacity) more efficient search can be reached when retrieval from LTM is automatized (Annac *et al.*, this issue). All of this points to a rich interplay between representations in VWM but also between VWM and information in LTM. An important overarching question is to what extent these qualities of VWM reflect rational responses to the inherent capacity limitations of the system and the qualities of our environment (cf. Anderson, 1991). VWM is tasked with keeping track of a visual environment in which it often makes sense to quickly extract global information (Liesefeld *et al.*, this issue), to lighten the attentional load (Morey, this issue), and to integrate information across saccades (Czoschke *et al.*, this issue). While this is likely often an efficient thing to do, this propensity may lead to a moderate amount of interference when the features of a probe become integrated with the representation they are aiming to test (Tabi *et al.*, this issue). Relatedly, to what extent do we make ideal use of both VWM and LTM in response to task demands? Representation in LTM might be beneficial in that it is less susceptible to distraction but it also appears to engender some loss of information, which may be a drawback in certain situations (Bae & Luck, this issue). Also, there may be situations in which observers do not use more efficient LTM-guided operations until forced to do so by task parameters (Annac *et al.*, this issue). We are a way off from being able to address these broader overarching questions, but the collection of articles here moves us forward on a number of fronts.

Acknowledgement

The authors are currently supported by Economic and Social Research Council (ESRC) grant 'Working memory across the adult lifespan: an adversarial collaboration (WoMAAC)' ES/N010728/1.

References

Adam, K. C., Vogel, E. K., & Awh, E. (2017). Clear evidence for item limits in visual working memory. *Cognitive Psychology*, *97*, 79–97. https://doi.org/10.1016/j.cogpsych.2017.07.001

Alvarez, G. A., & Thompson, T. W. (2009). Overwriting and rebinding: Why feature-switch detection tasks underestimate the binding capacity of visual working memory. *Visual Cognition*, *17*(1–2), 141–159. https://doi.org/10.1080/13506280802265496

Anderson, N. H. (1981). *Foundations of information integration theory*. New York, NY: Academic Press.

Anderson, J. R. (1991). Is human cognition adaptive? *Behavioral and Brain Sciences*, *14*(3), 471–485. https://doi.org/10.1017/S0140525X00070801

Annac, E., Zang, X., Müller, H. J., & Geyer, T. (this issue). A secondary task is not always costly: Context-based guidance of visual search survives interference from a demanding working memory task. *British Journal of Psychology*. https://doi.org/10.1111/bjop.12346

Bae, G.-Y., & Luck, S. J. (2017). Interactions between visual working memory representations. *Attention, Perception, & Psychophysics*, *79*(8), 2376–2395. https://doi.org/10.3758/s13414-017-1404-8

Bae, G.-Y., & Luck, S. J. (this issue). What happens to an individual visual working memory representation when it is interrupted? *British Journal of Psychology*. https://doi.org/10.1111/bjop.12339

Bae, G.-Y., Olkkonen, M., Allred, S. R., & Flombaum, J. I. (2015). Why some colors appear more memorable than others: A model combining categories and particulars in color working memory. *Journal of Experimental Psychology: General*, *144*(4), 744–763. https://doi.org/10.1037/xge0000076

Bays, P. M., Catalao, R. F., & Husain, M. (2009). The precision of visual working memory is set by allocation of a shared resource. *Journal of vision*, *9*(10), 7. https://doi.org/10.1167/9.10.7

Berggren, N., & Eimer, M. (this issue). Visual working memory load disrupts the space-based attentional guidance of target selection. *British Journal of Psychology*. https://doi.org/10.1111/bjop.12323

Bliss, D. P., Sun, J. J., & D'Esposito, M. (2017). Serial dependence is absent at the time of perception but increases in visual working memory. *Scientific Reports*, *7*(1), 14739. https://doi.org/10.1038/s41598-017-15199-7

Brady, T. F., & Alvarez, G. A. (2011). Hierarchical encoding in visual working memory: Ensemble statistics bias memory for individual items. *Psychological Science*, *22*(3), 384–392. https://doi.org/10.1177/0956797610397956

Brady, T. F., Konkle, T., & Alvarez, G. A. (2009). Compression in visual working memory: Using statistical regularities to form more efficient memory representations. *Journal of Experimental Psychology: General*, *138*(4), 487–502. https://doi.org/10.1037/a0016797

Brady, T. F., & Tenenbaum, J. B. (2013). A probabilistic model of visual working memory: Incorporating higher order regularities into working memory capacity estimates. *Psychological Review*, *120*(1), 85–109. https://doi.org/10.1037/a0030779

Couture, M., & Tremblay, S. (2006). Exploring the characteristics of the visuospatial hebb repetition effect. *Memory & cognition*, *34*(8), 1720–1729. https://doi.org/10.3758/BF03195933

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences*, *24*, 87–185. https://doi.org/10.1017/S0140525X01003922

Curby, K. M., Smith, S. D., Moerel, D., & Dyson, A. (this issue). The cost of facing fear: Visual working memory is impaired for faces expressing fear. *British Journal of Psychology*. https://doi.org/10.1111/bjop.12324

Czoschke, S., Fischer, C., Beitner, J., Kaiser, J., & Bledowski, C. (this issue). Two types of serial dependence in visual working memory. *British Journal of Psychology*. https://doi.org/10.1111/bjop.12349

Dodwell, G., Müller, H. J., & Töllner, T. (this issue). Electroencephalographic evidence for improved visual working memory performance during standing and exercise. *British Journal of Psychology*. https://doi.org/10.1111/bjop.12352

Donkin, C., Nosofsky, R., Gold, J., & Shiffrin, R. (2015). Verbal labeling, gradual decay, and sudden death in visual short-term memory. *Psychonomic Bulletin & Review*, *22*(1), 170–178. https://doi.org/10.3758/s13423-014-0675-5

Fischer, J., & Whitney, D. (2014). Serial dependence in visual perception. *Nature Neuroscience*, *17*(5), 738. https://doi.org/10.1038/nn.3689

Gosseries, O., Yu, Q., LaRocque, J. J., Starrett, M. J., Rose, N. S., Cowan, N., & Postle, B. R. (2018). Parietal-occipital interactions underlying control-and representation-related processes in working memory for nonspatial visual features. *Journal of Neuroscience*, *38*(18), 4357–4366. https://doi.org/10.1523/JNEUROSCI.2747-17.2018

Hardman, K. O., Vergauwe, E., & Ricker, T. J. (2017). Categorical working memory representations are used in delayed estimation of continuous colors. *Journal of Experimental Psychology: Human Perception and Performance*, *43*(1), 30–54. https://doi.org/10.1037/xhp0000290

Jiang, Y., Olson, I. R., & Chun, M. M. (2000). Organization of visual short-term memory. *Journal of Experimental Psychology: Learning, memory, and cognition*, *26*(3), 683. https://doi.org/10.1037/0278-7393.26.3.683

Liesefeld, H. R., Liesefeld, A. M., & Müller, H. J. (this issue). Two good reasons to say 'change!' – Ensemble representations as well as item representations impact standard measures of VWM capacity. *British Journal of Psychology*. https://doi.org/10.1111/bjop.12359

Logie, R. H. (1995). *Visuo-spatial working memory*. Hove, UK: Lawrence Erlbaum.

Logie, R. H., Brockmole, J. R., & Vandenbroucke, A. R. (2009). Bound feature combinations in visual short-term memory are fragile but influence long-term learning. *Visual Cognition*, *17*(1–2), 160–179. https://doi.org/10.1080/13506280802228411

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, *390*, 279–281. https://doi.org/10.1038/36846

Morey, C. C. (2018). The case against specialized visual-spatial short-term memory. *Psychological Bulletin*, *144*(8), 849–883. https://doi.org/10.1037/bul0000155

Morey, C. C. (this issue). Perceptual grouping boosts visual working memory capacity and reduces effort during retention. *British Journal of Psychology*. https://doi.org/10.1111/bjop.12355

Morey, C. C., Cong, Y., Zheng, Y., Price, M., & Morey, R. D. (2015). The color-sharing bonus: Roles of perceptual organization and attentive processes in visual working memory. *Archives of Scientific Psychology*, *3*(1), 18–29. https://doi.org/10.1037/arc0000014

Olson, I. R., & Jiang, Y. (2004). Visual short-term memory is not improved by training. *Memory & Cognition*, *32*(8), 1326–1332. https://doi.org/10.3758/BF03206323

Pashler, H. (1988). Familiarity and visual change detection. *Perception and Psychophysics*, *44*(4), 369–378. https://doi.org/10.3758/BF03210419

Pollmann, S. (this issue). Working memory dependence of spatial contextual cueing for visual search. *British Journal of Psychology*. https://doi.org/10.1080/13506285.2011.630694

Pratte, M. S., Park, Y. E., Rademaker, R. L., & Tong, F. (2017). Accounting for stimulus-specific variation in precision reveals a discrete capacity limit in visual working memory. *Journal of Experimental Psychology: Human Perception and Performance*, *43*(1), 6–17. https://doi.org/10.1037/xhp0000302

Reinhart, R. M., & Woodman, G. F. (2013). High stakes trigger the use of multiple memories to enhance the control of attention. *Cerebral Cortex*, *24*(8), 2022–2035.

Rhodes, S., & Cowan, N. (2018). Attention in working memory: Attention is needed but it yearns to be free. *Annals of the New York Academy of Sciences*, *1424*(1), 52–63. https://doi.org/10.1111/nyas.13652

Rhodes, S., Cowan, N., Hardman, K., & Logie, R. (2018). Informed guessing in change detection. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *44*(7), 1023–1035. https://doi.org/10.1093/cercor/bht057

Ricker, T. J., & Hardman, K. O. (2017). The nature of short-term consolidation in visual working memory. *Journal of Experimental Psychology: General*, *146*(11), 1551–1573. https://doi.org/10.1037/xge0000346

Rouder, J. N., Morey, R. D., Morey, C. C., & Cowan, N. (2011). How to measure working memory capacity in the change detection paradigm. *Psychonomic Bulletin & Review*, *18*(2), 324–330. https://doi.org/10.3758/s13423-011-0055-3

Rouder, J. N., Thiele, J. E., Province, J. M., Cusumano, M., & Cowan, N. (2014). *The evidence for a guessing state in working memory judgments*. Unpublished manuscript. Retrieved from http://pcl.missouri.edu/node/134

Sauseng, P., Peylo, C., Biel, A. L., Friedrich, E. V., & Romberg-Taylor, C. (this issue).Does cross-frequency phase coupling of oscillatory brain activity contribute to a better understanding of visual working memory? *British Journal of Psychology*. https://doi.org/10.1111/bjop.12340

Schneegans, S., & Bays, P. M. (this issue). New perspectives on binding in visual working memory. *British Journal of Psychology*. https://doi.org/10.1111/bjop.12345

Shimi, A., & Logie, R. H. (2018). Feature binding in short-term memory and long-term learning. *Quarterly Journal of Experimental Psychology*, online ahead of print.

Souza, A. S., Rerko, L., & Oberauer, K. (2016). Getting more from visual working memory: Retro-cues enhance retrieval and protect from visual interference. *Journal of Experimental Psychology: Human Perception and Performance*, *42*(6), 890–910. https://doi.org/10.1037/xhp0000192

Suchow, J. W., Fougnie, D., Brady, T. F., & Alvarez, G. A. (2014). Terms of the debate on the format and structure of visual memory. *Attention, Perception, & Psychophysics*, *76*(7), 2071–2079. https://doi.org/10.3758/s13414-014-0690-7

Tabi, Y., Husain, M., & Manohar, S. (this issue). Recall cues interfere with retrieval from visuospatial working memory. *British Journal of Psychology*. https://doi.org/10.1111/bjop.12374

van den Berg, R., Shin, H., Chou, W.-C., George, R., & Ma, W. J. (2012). Variability in encoding precision accounts for visual short-term memory limitations. *Proceedings of the National Academy of Sciences*, *109*(22), 8780–8785. https://doi.org/10.1073/pnas.1117465109

Woodman, G. F., Vogel, E. K., & Luck, S. J. (2012). Flexibility in visual working memory: Accurate change detection in the face of irrelevant variations in position. *Visual Cognition*, *20*(1), 1–28. https://doi.org/10.1080/13506285.2011.630694

Received 7 January 2019; revised version received 19 January 2019