Published in final edited form as:

Atten Percept Psychophys. 2014 October ; 76(7): 1861–1870. doi:10.3758/s13414-014-0783-3.

Introduction to the Special Issue on Visual Working Memory

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Abstract

Objects are not represented individually in visual working memory (VWM), but in relation to the contextual information provided by other memorized objects. We studied whether the contextual information provided by the spatial configuration of all memorized objects is viewpoint-dependent. We ran two experiments asking participants to detect changes in locations between memory and probe for one object highlighted in the probe image. We manipulated the changes in viewpoint between memory and probe (Exp. 1: 0°, 30°, 60°; Exp. 2: 0°, 60°), as well as the spatial configuration visible in the probe image (Exp. 1: full configuration, partial configuration; Exp. 2: full configuration, no configuration). Location change detection was higher with the full spatial configuration than with the partial configuration or with no spatial configuration at viewpoint changes of 0°, thus replicating previous findings on the nonindependent representations of individual objects in VWM. Most importantly, the effect of spatial configurations decreased with increasing viewpoint changes, suggesting a viewpoint-dependent representation of contextual information in VWM. We discuss these findings within the context of this special issue, in particular whether research performed within the slots-versus-resources debate and research on the effects of contextual information might focus on two different storage systems within VWM.

In May of 2013, there was a well-attended symposium on “The Structure of Visual Working Memory” at the annual meeting of the Visual Sciences Society. Based on the interest shown during that session, we decided to organize a special issue on Visual Working Memory in *Attention, Perception, and Psychophysics*. Now, I am happy to offer this special issue to the readers of AP&P.

As Luck and Vogel (2013) say in their useful 2013 review of the topic, “the term working memory is used in many different ways”. However, those multiple uses of the term do have a common core. Visual working memory (VWM) is generally taken to be a volatile, limited-capacity memory that serves a current task. The tasks might include integration of information across saccades (e.g. Hollingworth, Richard, & Luck, 2008), detection of change between two stimuli, separated in time (e.g. Wolfe, Reinecke, & Brawn, 2006), or holding the target ‘template’ in a visual search task (e.g. Soto, Humphreys, & Heinke, 2006).

While a rich set of roles has been proposed for VWM, a very substantial proportion of the data on the topic has come from a rather impoverished set of stimuli. In a world laden with items to hold in VWM, much of what we know comes from experiments in which Os are asked to remember some small set of colored squares. First popularized by in Luck and Vogel’s (1997) influential paper, Os are shown an initial, memorization array as in Fig 1a.

Then, following a blank retention period (1b), typically of about a second, those Os are asked in any of a number of ways to determine if the test stimulus (1c) is the same as the initial, memorized stimulus. Later, Zhang and Luck (2008) introduced a method where, after memorizing (1d) and retaining (1e) an array of items, Os indicated the color of one of those items by adjusting a cursor on a color wheel (1f). In this way, the precision of the memory representation could also be ascertained.

In the context of tasks like those just described, VWM seems clearly defined. However, when we think about what VWM might be used for in the world, as discussed earlier, things become less clear. Consider the role of VWM in visual search. It is clear that the contents of VWM can influence search (Soto et al., 2006) (Cosman & Vecera, 2011). Recent evidence indicates that only one item in VWM can capture visual attention (van Moorselaar, Theeuwes, & Olivers, 2014; but see A. L. Gilchrist & Cowan, 2011). Based on work of this sort, it has been suggested that VWM contains the representation of the current target of search – the search ‘template’ (Olivers, Peters, Houtkamp, & Roelfsema, 2011). However, it is a bit too simple to think that the current instruction to your search engine is simply deposited in VWM from whence it guides your search. For example, in search for specific real-world objects (find this cat, that toaster, etc), it is possible to have Os search for any of, literally, hundreds of distinct possible targets at the same time in a task known as “hybrid search” (Wolfe, 2012, Cunningham & Wolfe, 2012). The sheer number of these potential targets takes the storage and maintenance of this target set out of the realm of VWM. Moreover, the memory representations of these targets can last for many minutes or more, violating the temporal limits on VWM as usually defined. Finally, it is possible to load VWM with colored boxes as in Fig 1a without disrupting this multiple target visual search (Drew, Boettcher, & Wolfe, 2013) even though other kinds of searches can interact antagonistically with VWM (e.g. Cain & Mitroff, 2013; Emrich, Al-Aidroos, Pratt, & Ferber, 2010).

It appears that a large set of possible target items can live in some ‘activated long term memory’, or ALTM (Cowan, 1995). VWM may be a short-term buffer between ALTM and the search task. This is implied in Oberauer’s “three-embedded-components model” (Oberauer & Hein, 2012) but it remains for the future to reveal the details of how LTM, ALTM, VWM, and search work together. In any case, on the one hand VWM seems intimately, perhaps mandatorily, involved in tasks like visual search while, on the other hand, in some situations, those tasks seem able to avoid the limitations of VWM.

This points to the fact that it is not always trivial to discriminate the VWM representation of a stimulus from other representations. For instance, in Wolfe et al (2006), our observers looked at a set of 20 colored dots. At some point, while they were looking at the dots, one dot was cued by an increase in brightness. It could also change color at that moment. O’s were asked to say whether the cued dot had changed color or not. Their detection of the change was very close to chance. This poor performance was consistent with an ability to monitor the color of no more than 4 of the 20 items, in spite of the fact that the dots were fully visible the whole time. This capacity limit on the ability to keep track of clearly visible items is very similar to the capacity limits seen in VWM experiments. A similar point has been made about the limits on the ability to track clearly visible, moving items in the

Multiple Object Tracking paradigm (Alvarez & Cavanagh, 2005). While monitoring a set of visible stimuli would not normally be thought of as a *memory* task, it might be that VWM limits also serve as a limit on our ability to attend to visible stimuli. This blurs the line between remembered and visible stimuli. Other experiments blur the line between VWM and LTM. The transitions and relations between VWM to a longer-term storage continue to be topics of active study (Endress & Potter, 2014).

These complexities notwithstanding, visual working memory is a booming topic in the field of visual cognition. This can be seen if we plot the number of papers on the topic as registered by “Web of Science” (Figure 2).

As we know, the volume of scientific publication is increasing overall, so it could be that there is nothing special about the rise in papers on VWM. Maybe every topic is booming in the same way. As something of a test of the hypothesis that VWM is, indeed, a trending topic in the field, I inquired about other topics that have been important in my own work over the years. I looked for topics with roughly comparable numbers of total papers (1000–1500). For purposes of illustration, I have plotted results for Visual Aftereffects and for a combination of Change Blindness (Simons & Rensink, 2005) and Inattentional Blindness (Mack & Rock, 1998). Visual aftereffects were a hot topic in the 1970s and have settled down to a rate of 30–40 papers per year over the last 20 yrs. Change and Inattentional Blindness are interesting because they came on the scene as research topics at about the same time as VWM but while the Blindness topics rose at about the same rate as VWM for about 15 years, they may have peaked a few years back while VWM output keeps increasing.

This special issue adds to that tally. What else, beyond mere numbers, will this issue contribute? I will say a word about each of the papers with the intention to whet your appetite for more extended reading. Some of the papers add to our understanding of the properties of VWM. Others are directed at theoretical issues, usually trying to decide between “slot” and “resource” models. Slot models are those that propose that WM capacity is limited because there is a limit on the number of discrete representations that can be held in WM. The usual estimate is that there are 3–5 slots to hold these representations. Resource models propose that WM is more continuous. There is an amount of WM available but it can be allocated flexibly with the quality of the representation varying as a function of the amount of resource devoted to that representation. Some papers serve both empirical and theoretical functions. The papers are roughly organized to place those concerned with the properties of VWM toward the beginning with the theoretical pieces toward the end of the issue.

Properties of Working Memory

Olivers and Schreij (2014) deal with the relationship of color and location in the classic VWM task. They are trying to connect the color memory task of Figure 1 more closely to the situation of the real world. They note that stimuli do not usually appear and disappear in a flash as they do in the standard VWM memorization phase. In the world, you turn a corner and see something new or the dynamic scene in front of you evolves, revealing new stimuli.

As a step toward situations of that sort, Olivers and Schreij had their colored patches appear and disappear behind a virtual brick wall. They found that, as long as performance was off the ceiling and off the floor, their Os did better if the test display emerged in the same way that the original display had emerged. Thus, memory for the mode of appearance had an influence on the standard measures of VWM capacity.

In a different modification of the standard paradigm, Kool, Conway, and Turk-Browne (2014) asked what would happen in the color patch paradigm, illustrated in Figure 1d–f, if the color patches were presented sequentially? This turns the classic VWM experiment into something more like the even more classic digit span or word list methods that have been long used for investigating Short Term Memory. Kool, et al. report that spreading the memorization stage (Fig 1d) over time produces strong recency effects; at least, when the set size gets larger than the standard VWM capacity of 3–4 items. If, instead of presenting five colored squares in a single flash, they presented them one after another, each in their own location, the last item presented was the most accurately recalled when its location was probed. Primacy effects are much less marked. The first item presented got only a modest boost. It looks a bit like a push-down stack: the item added to the top of the stack is remembered best and the earlier items get pushed out by the more recent ones. One perhaps surprising aspect of the results of Kool et al. is that the precision of the memory, as measured with the color wheel method of Fig 1f, does not show much change with serial position. There is more evidence for swaps between the earlier items on the list. You are cued for the item at location A, but you erroneously report the color of the item that was presented at location B. These results have a rather discrete slot-like feel to them but versions of resource models actually fit the data about as well.

Continuing with tasks that ask about particular colors in particular locations, Rajsic and Wilson (2014) document an interesting asymmetry. In many VWM tasks, Os are asked about the color of an item in a specific location or the location of an item of a specific color. These are not equivalent tasks. You do better if you are asked where the green item had been located than if you are asked which item had been green. Pertzov and Masud (2014) make a related point in their contribution. They find that previous objects in a location interfere with memory for the current object in that location, while previous objects sharing features other than location, such as color and orientation, do not. These studies are reminiscent of an earlier visual attention literature on the status of location. Was location a “feature” like color or orientation or was it somehow different? As in the present VWM papers, the general conclusion of the older literature was that location was a different sort of feature (Kwak & Egeth, 1992; Nissen, 1985; Tsal & Lavie, 1988) though opinion was not unanimous on this point (Bundesen, 1991).

Location may be a special sort of feature, but that does not mean that all other features form a homogeneous family. This has been a mistake in the study of visual attention. While it is true that some rules apply across features (e.g. Duncan & Humphreys, 1989) in other cases, a rule that applies, for example, to color might not apply to size (e.g. Bilsky & Wolfe, 1995). A similar situation arises in VWM. Just because you understand how things work with stimuli defined by one property does not mean that you understand how they apply to another. Xing et al. (2014) report new findings about the representation of contrast in VWM.

The representation of some features like spatial frequency seems to be stable over fairly long periods of times (c.f. Magnussen and Greenlee, 1994). The precision of other representations degrades more rapidly. Contrast turns out to be a feature that degrades. Xing et al. are interested in whether the representation of contrast is abstract or is stored as the contrast of a specific spatial pattern. They find that VWM is more robust when the spatial arrangements do not change between exposure and test, suggesting that the representation is fairly specific.

Clevenger and Hummel (2014) expand the question of encoded features to include relationships between items in VWM. Suppose you encode a big red square and a small blue triangle. What do you know about their relationship to each other? Do you know that the square is to the left of the triangle? Do you know how much bigger the square is? If you know these things, does each of these added bits of information take up space in VWM in some fashion? The core of the Clevenger and Hummel argument is that “encoding a pair of objects in WM entails encoding all the relations between that pair at no additional cost”. This claim is similar to the original Luck and Vogel (1997) claims about features in VWM. They held that you encoded discrete objects and that you got all the features of an encoded object as part of a package deal. That is, a big red vertical object was one object in VWM, not three features. Others have challenged the strong form of that claim (Cowan, Blume, & Saults, 2013). Similarly, it might turn out that there are limits on the “free” encoding of relationships between objects, but it is important to recognize that a limited capacity VWM contains more than just the identities of 3 or 4 objects.

We tend to think of VWM as a single construct whose properties we are trying to unravel. At any moment, VWM might store four colored patches or four of more complex conjunctions of features as in the Clevenger and Hummel work, or, perhaps, four real world objects. The burden of a literature review by Bancroft et al. (2014) is that those stimuli might be represented in different neural substrates (c.f. Yu and Chun, 2006). FMRI and EEG experiments have localized evidence for VWM storage in pre-frontal cortex and in sensory / task-specific cortex. Bancroft et al argue that stimulus complexity is one (but not the only) factor that determines which part of the brain will hold any specific set of VWM stimuli. What goes where? We are used to thinking of a hierarchy in which simple visual properties are represented at early stages of cortical processing with the frontal lobes handling more complex material. Here the results point in the opposite direction. Simple VWM stimuli seem to be preferentially held in pre-frontal cortex with more complex stimuli apparently requiring the more specialized work of sensory / task-specific cortex. That said, behavioral data does not support the existence of independent VWM stores for complex and simple stimuli. We cannot increase WM capacity to 8 by storing 4 color patches and 4 complex conjunctions. The distinct geography of simple and complex VWM described here must still be subject to some common capacity limitation.

There is more of an argument to be made for modality-specific WM stores (Baddeley’s (1974) phonological loop and visuo-spatial sketchpad, for instance). VWM is, by definition, “visual” but, of course, what gets encoded into memory need not be restricted to the visual modality. Salmela et al (2014) try to determine if auditory and visual items are held in the same working memory or in separate auditory and visual working memory stores, as in the

Baddeley (1974) formulation. Their method involves looking at the precision of memory as a function of the number of items held in memory. Holding two visual spatial frequencies or two auditory tones in memory reduces precision of memory compared to just holding a single item. Salmela et al. report that holding one spatial frequency and one auditory tone at the same time exacts the same cost as holding two auditory or two visual stimuli. They argue that WM is a cross-modal resource. Like other debates in this field (parallel vs serial visual search, slots and resources in WM), this question will not be settled by any single experiment. Indeed, it seems likely, as Fougne and Marois (2011) suggest, that WM is limited by both modality-specific and cross-modality factors and that the pattern of results will depend on the specific methods used.

It is worth noting that, while precision and capacity are each used as measures of VWM, they are not measures of exactly the same thing. Lorenc and colleagues (2014) use memory for faces to make this point. Their observers saw a sequence of faces, each in its own specific location and were then probed for one of those faces. The number of faces in the sequence could vary. This method allowed the authors to get a measure of how many faces were held in memory and it allowed them to measure the precision of the memory. They performed this experiment with upright and inverted faces. This revealed a dissociation between capacity and precision because the number of faces held in memory did not change as a function of inversion, but the precision was lower for the inverted faces.

In their contribution, Konstantinou et al. (2014) use WM as a way to test predictions of Load Theory (Lavie, 2005). Load effects are often measured with flanker tasks. A target letter is mapped to one response key. How much interference do you get from a distractor that is mapped to another response key? The classic Load Theory finding is that increasing task difficulty reduces the interference from the distractor as more attentional resources are devoted to the target. In the Konstantinou et al. experiments, this is the pattern of results that you get if you impose a WM encoding load at the same time as the flanker task. Interestingly, you get the opposite result if the flanker task comes during WM maintenance. In this version, the WM load (e.g. the set of colored boxes) is presented well before the flanker task. The act of holding the items in WM makes observers more subject to the interfering effects of the distractor in the flanker task.

Two of the Special Issue papers deal with individual differences. The first, by Mall et al. (2014) is a good example of a useful null result. As will be seen, later in this issue, there is lots of evidence for a close relationship between VWM and visual attention. Attention can be drawn to items held in VWM (Downing & Dodds, 2004; Soto, Hodsoll, Rotshtein, & Humphreys, 2008). There are strong claims that the attentional template for tasks like visual search resides within WM (Olivers et al., 2011). Thus, it might seem reasonable that WM capacity would be related to tasks, like change detection, that make significant demands on visual attention. Mall et al. looked for evidence that WM capacity was related to the ability to filter out information not relevant to the current task but found no evidence for this. Models without a WM component fit the data better than models including WM. The other paper, by Ko et al (2014), dealing with individual differences, concerns behavioral and neurophysiological (ERP) measures of the effects of aging on change detection. They measured evoked potentials while their participants did a version of the usual color patch

paradigm. Perhaps the most interesting aspect of the Ko et al. results is a dissociation between Contralateral Delay Activity (CDA) and WM capacity measures in older adults. The CDA signal has been taken as an electrophysiological measure of the current contents of WM and of its total capacity (Vogel & Machizawa, 2004) so it is interesting that the authors report that they “found a clear dissociation between the behavioral capacity estimates and the CDA”. Even though behavioral capacity was lower in the older observers, the CDA was not. They speculate that the difference between younger and older observers may lie in the quality and not the quantity of VWM representations.

Gilchrist and Cowan (2014), report a result that points to an interesting parallel between search in VWM and search through visual stimuli (though, it should be noted, this is not the main point that they make in the paper). Their observers perform a change detection task in which they see a collection of colored patches and must subsequently decide if a test probe was or was not present in the display. As the memory set size is varied, the $RT \times$ set size function is shallower for new probes (novel colors) than for old probes. Gilchrist and Cowan argue that this runs counter to models of WM. Interestingly, it is very similar to what might be seen in a visual search experiment. If we take the novel colors to be the search target, then this follows the common rule that target-present RTs are generally faster than target-absent RTs and that target-present $RT \times$ set size slopes are shallower. At small set sizes, Gilchrist and Cowan find that the new probes produce slopes near 0 msec/item while the old probes produce relatively steep slopes. This is a pattern that is seen with some simple feature searches in visual search (Searches where the target is defined by a unique feature; e.g. color). If the feature search is not very easy, the target present slopes are often near zero while observers appear to do something more like a serial search for the absent trials (Wolfe, 1998). We can speculate that in these cases observers don't quite trust the signal that guides them to targets, so when there is no signal, they laboriously scrutinize the display to be sure that no target is present

Pan et al. (2013) asked if WM could have an influence on perception outside of awareness. To examine this question, they used the continuous flash suppression (CFS) methodology in which a salient, dynamic pattern in one eye effectively suppresses awareness of any stimulus in the other eye (Tsuchiya & Koch, 2005). They presented a face to observers for a later memory test. Then they started the CFS and slowly ramped up the contrast of a face in the suppressed eye. The face could be the old one or a new one and the critical measure was time until the face broke through the suppression to reach awareness. The face held in VWM broke through faster than a new face. This turned out to be the case even if the first presentation of the face was masked. Thus, a face that was unseen was coded into VWM and shortened the time required to break CFS. Importantly, the effect doesn't appear if you don't have to memorize the initial face for a later memory test. Thus, VWM can operate below the radar of visual awareness. This makes a degree of intuitive sense since, if you are looking for an object, say a pepper grinder, you are typically not aware of any visible template of that object. Indeed, you might have forgotten that you were explicitly looking for the item, realizing it only once you have found it.

Given that VWM stimuli influence other processes and are being influenced, in their turn, outside of awareness, one might be forgiven for feeling that contents of VWM are

promiscuously interacting with everything, while the conscious “owner” of that VWM is occupied elsewhere. Quak (2014) provide a useful negative finding to undercut this completely undifferentiated view of what is going on “under the hood”. They had individuals remembering objects that would require either a “precision grip” (like picking up a paper clip) or a “power grip” (like wielding a hammer). They also included objects that were never going to be picked up at all (like a bridge). Concurrent with the VWM task, they had observers engage in precision or power motor tasks in order to see if the motor task interacted with the VWM in an object-specific manner. The short answer is that, over a couple of experiments, there was no sign that doing a precision task interacted with memory for a paperclip any more than with memory for a bridge or hammer. Of course, this is a negative finding but they make an argument that the studies are sufficiently powered to see an effect if it were present. They conclude that VWM does not make use of motor affordances when storing manipulatable objects. Thus there are some input streams that do not seem to interact with VWM.

Theoretical Matters: Slots, Resources, et al

Turning to theories of visual working memory, it is clear that the VWM is limited in its capacity, but how should we think about those limits? The theoretical landscape has been defined by two apparently opposing views. Luck and Vogel (1997) imagined that there were about four discrete “slots” into which one could place items to be held in VWM. Much of the work in the field is framed by an assumption that there is a “magical number” of about four somethings (Cowan, 2001). Others, for example, Alvarez and Cavanagh (2004) and Wilken and Ma (2004) argued for a continuous “resource” that could be divided over an arbitrary number of objects in VWM. As you gave less and less resource to an item, you got a poorer and poorer representation of that item in memory.

Ten years (or so) later, this debate has taken on something of the feel of other seemingly dichotomous debates in our field: serial vs parallel arguments in visual search, nature vs nurture more broadly, among others. Over time, the models tend to become more nuanced and the truth, as best we can see it, seems to incorporate aspects of both. This doesn’t mean that the topic is either settled or uninteresting. It means that spectators in the VWM debate should not expect a knock-out blow that leaves either slots or resources standing victorious.

The more theoretically-focused articles in this special issue illustrate some of the richness of the current intellectual landscape. Suchow et al. (2014) get us away from simple-minded slots vs resources dichotomies by offering a taxonomy based on “ 7 ± 2 core questions” (7 ± 2 equals 8 in this case). Some of these questions are largely orthogonal to the slots vs resources issue. Others illustrate how the slot and resource approaches could blend into one another. For example, suppose you proposed that there was some level of discrete quantization in VWM. For the sake of argument, let’s say that there were 24 VWM quanta. If you can assign those at will to different items, this will look a lot like a resource model. Methods available to us are unlikely to tell the difference between a 24 quanta story and a completely continuous resource. If we suppose that assigning just 1 or 2 quanta to an item does not produce a reliable VWM representation, we will rapidly get to something that looks slot-like. Suppose that a reliable VWM representation requires 4 quanta. If you were very

precise, you could squeeze 6 items into VWM. If some items grabbed 5 or 6 quanta, you would produce something resembling a slot-like 4 item limit. The preceding example is derived from Fig 1 and Question 2 of Suchow et al. and is not intended as a real model. It merely illustrates that it would not be that hard to have an underlying structure that appeared like slots in one experiment and resources in another.

The paper by Souza and colleagues (2014) can serve as an illustration of the theoretical questions that hide within the dichotomous slots/resources debate. In the standard, color patch experiment, suppose that an observer is holding a reddish item and a bluish item in VWM. If a probe is presented at one of the two locations, the observer can be asked whether the item at that location was the red one or the blue one. The observer can also be asked to use a color wheel or other method to attempt to reproduce the exact shade of red (Fig 1f). The memories, supporting those two outputs could be dissociable. One might remember the red quite exactly but mislocalize it to the other location or one might know that this location held the red item but be very imprecise about the precise hue. Souza et al demonstrate this dissociation by delaying the time between the probe and the time of report. Once a probe has been presented, the chance of a transposition error during a subsequent delay is reduced but the precision of the color judgment continues to decline. The authors' modeling work argues that either slot or resource models need to represent the precision of location separately from the precision of the color representation. In this case, the data do not decide between models but show how both classes of models can accommodate a richer representation in VWM.

One approach to attempting to choose between discrete slot and continuous resource styles of modeling of VWM is to seek improved methods for distinguishing between the predictions of those models. Donkin, Tran, and Nosovsky (2014) make use of "landscaping analysis of the ROC predictions" from slots and resource models. The work is an extension of Rouder et al (2008), who argued in favor of discrete slots. The present paper "did not point to a clear-cut winning model". Donkin et al. report on four different experiments. Three of them point toward slots but one strongly supported their continuous alternative. One conclusion that seems to follow is that the details of the experimental methods can be very important when trying to pick the best model in this area.

Another illustration of the difficulty in distinguishing between slots and resources comes from van den Berg and Ma's (2014) paper in this issue. "Plateau" methods are one of the standards in VWM studies. A measure of how many items are remembered is plotted against Memory set size. For small memory set sizes, the amount remembered rises with the set size. At some point, that rise levels off to a plateau that is taken as a measure of VWM capacity (perhaps with some correction for guessing and so forth). The presence of an inflection point between the rising and plateau portion of the curve is often cited as slot-friendly evidence. Resources, it is reasoned, should not yield a two-part curve. Using simulated data from slotted and slotless models, van den Berg and Ma argue that this logic is wrong. Again, the argument is reminiscent of earlier debates in the visual search literature where $RT \times$ set size patterns that were thought to be clear evidence for "serial" models, turned out to be ambiguous (Thornton & Gilden, 2007; Townsend & Wenger, 2004).

In the end, slots and resources are metaphors. No one would expect to open up the brain and find slots, like parking spots, in some specific location in the brain. One approach to modeling in this area is to drop the terms and formulate a different class of model. That is the choice of Johnson, Simmering, and Buss (2014). In the place of slot and resource metaphors for VWM representations, they offer a model based on neural dynamics. Swan and Wyble's (2014) paper can be seen as a different effort in the same spirit. At the heart of their model is a neural network dubbed the "binding pool" that links "types" of specific features (red, oblique, etc) to specific object "tokens". The tokens have a slot-like feel to them. The pool is more like a continuous resource and the heart of the paper illustrates how this architecture can produce the fundamental phenomena of the VWM field.

At the beginning of this introduction, I called the standard colored box VWM stimuli "impoverished". It is fitting to end the Special Issue with Orhan and Jacobs' (2014) paper making this point with much more depth and rigor. They argue we aren't really that interested in explaining memory for a few isolated items. We want to know how people operate in the real world. In the end, they remind us, this will require ecologically valid stimuli. In our daily life, we operate in a world of rich, continuous scenes where you can't actually count the set size (Neider & Zelinsky, 2008; Wolfe, Alvarez, Rosenholtz, Kuzmova, & Sherman, 2011; Yu, Samaras, & Zelinsky, 2014). They argue that the standard, laboratory paradigms for studying VWM may significantly underestimate its capacity because, in the real world, our understanding of natural scene statistics allows us to do much more than we can do with 4 colored boxes or even 4 isolated objects. They set forth a program that can move us closer to an understanding of VWM in the wild.

Finally, in an excess of efficiency, we inadvertently published a couple of Short reports that were intended to be printed in the special issue. We will reproduce their abstracts below and we invite readers to seek out the whole paper elsewhere. Tollner et al (2014) were interested in the question of whether each item in WM is coded independently or not. They had Os memorize set of singleton items. These could all be singletons in the same dimension (e.g. red, yellow, and green items amidst blue distractors. Alternatively, each singleton could be defined by a unique value on a different dimension: the red item, the big item, than the tilted item, for example. Tollner and colleagues found that the task was a little more difficult if the items varied across dimensions. This is interesting because it suggests that the memory of the big, red, vertical item is dependent on other items and is not entirely independent. Tollner et al investigate some of the neural underpinnings of this effect using the CDA – contralateral delay activity – measure that has been so useful in VWM research.

The second Short Report that we published in advance also concerns the independence of the representation of items in VWM. Like the Töllner paper, it concludes that items are not coded in isolation. In this paper, Papenmeier and Huff (2014) address this question in a study of the role of spatial context in VWM (c.f. the Olivers and Schreij paper, discussed earlier). Papenmeier and Huff have long been interested in the viewpoint dependence/independence of visual representations (Huff, Meyerhoff, Papenmeier, & Jahn, 2010). Here, their Os memorize arrays of objects sitting on a slanted plane. When the view of that plane is changed, performance declines even though the objects are all still visible and recognizable. As in other papers in this special issue, an important takeaway message is that

VWM items are stored in a context, not in splendid isolation (see also Brady & Tenenbaum, 2013).

We hope you find the Special Issue stimulating and useful. If you do, keep an eye out for another special issue on Working Memory due to be published in a few months in our sister journal, *Memory and Cognition*.

The Abstracts of the Published Reports

Töllner, T., Eschmann, K. J., Rusch, T., & Müller, H. (2014). Contralateral delay activity reveals dimension-based attentional orienting to locations in visual working memory. *Attention, Perception, & Psychophysics*, 76(3), 655–662. doi: 10.3758/s13414-014-0636-0

Published Abstract

In research on visual working memory (WM), a contentiously debated issue concerns whether or not items are stored independently of one another in WM. Here we addressed this issue by exploring the role of the physical context that surrounds a given item in the memory display in the formation of WM representations. In particular, we employed bilateral memory displays that contained two or three lateralized singleton items (together with six or five distractor items), defined either within the same or in different visual feature dimensions. After a variable interval, a retro-cue was presented centrally, requiring participants to discern the presence (vs. the absence) of this item in the previously shown memory array. Our results show that search for targets in visual WM is determined interactively by dimensional context and set size: For larger, but not smaller, set sizes, memory search slowed down when targets were defined across rather than within dimensions. This dimension-specific cost manifested in a stronger contralateral delay activity component, an established neural marker of the access to WM representations. Overall, our findings provide electrophysiological evidence for the hierarchically structured nature of WM representations, and they appear inconsistent with the view that WM items are encoded in isolation.

Papenmeier, F., & Huff, M. (2014). Viewpoint-dependent representation of contextual information in visual working memory. *Attention, Perception, & Psychophysics*, 76(3), 663–668. doi: 10.3758/s13414-014-0632-4

REFERENCES

- Alvarez GA, Cavanagh P. The capacity of visual short-term memory is set both by visual information load and by number of objects. *Psychol Sci*. 2004; 15(2):106–111. [PubMed: 14738517]
- Alvarez GA, Cavanagh P. Independent Resources for Attentional Tracking in the Left and Right Visual Hemifields. [Article]. *Psychological Science* (Wiley-Blackwell). 2005; 16(8):637–643.
- Baddeley, AD.; Hitch, G. Working Memory. In: Bower, GH., editor. *The psychology of learning and motivation*. Vol. 8. NY: Academic Press; 1974. p. 47-89.
- Bancroft T, Hockley W, Servos P. Does stimulus complexity determine whether working memory storage relies on prefrontal or sensory cortex? *Attention, Perception, & Psychophysics*. 2014:1–8.
- Bilsky AA, Wolfe JM. Part-whole information is useful in size X size but not in orientation X orientation conjunction searches. *Perception and Psychophysics*. 1995; 57(6):749–760. [PubMed: 7651800]

- Brady TF, Tenenbaum JB. A Probabilistic Model of Visual Working Memory: Incorporating Higher Order Regularities Into Working Memory Capacity Estimates. *Psychological Review*. 2013; 120(1): 85–109. [PubMed: 23230888]
- Bundesden C. Visual selection of features and objects: Is location special? A reinterpretation of Nissen's (1985) findings. *Perception and Psychophysics*. 1991; 50(1):87–89. [PubMed: 1881770]
- Cain MS, Mitroff SR. Memory for found targets interferes with subsequent performance in multiple-target visual search. *J Exp Psychol Hum Percept Perform*. 2013; 39(5):1398–1408. [PubMed: 23163788]
- Clevenger P, Hummel J. Working memory for relations among objects. *Attention, Perception, & Psychophysics*. 2014:1–21.
- Cosman J, Vecera S. The contents of visual working memory reduce uncertainty during visual search. *Attention, Perception, & Psychophysics*. 2011; 73(4):996–1002.
- Cowan, N. *Attention and Memory: An integrated framework*. New York: Oxford U press; 1995.
- Cowan N. The magical number 4 in short-term memory: a reconsideration of mental storage capacity. *Behav Brain Sci*. 2001; 24(1):87–114. discussion 114–185. [PubMed: 11515286]
- Cowan N, Blume CL, Saults JS. Attention to Attributes and Objects in Working Memory. *J Exp Psychol Learn Mem Cogn*. 2013; 39(3):731–747. [PubMed: 22905929]
- Cunningham, CA.; Wolfe, JM. Extending “Hybrid” Visual X Memory Search To Very Large Memory Sets And To Category Search; Paper presented at the Annual meeting of the Psychonomic Society; 2012.
- Donkin C, Tran S, Nosofsky R. Landscaping analyses of the ROC predictions of discrete-slots and signal-detection models of visual working memory. *Attention, Perception, & Psychophysics*. 2014:1–14.
- Downing P, Dodds C. Competition in visual working memory for control of search. *Visual Cognition*. 2004; 11(6):689–703.
- Drew, T.; Boettcher, S.; Wolfe, JM. Hybrid Visual and Memory Search Remains Efficient When Visual Working Memory is Full. paper presented at the Annual Meeting of the Psychonomic Society, Toronto(abs 207); 2013. p. 11/14-17/13.
- Duncan J, Humphreys GW. Visual search and stimulus similarity. *Psychological Review*. 1989; 96:433–458. [PubMed: 2756067]
- Emrich SM, Al-Aidroos N, Pratt J, Ferber S. Finding memory in search: the effect of visual working memory load on visual search. *Q J Exp Psychol (Hove)*. 2010; 63(8):1457–1466. [PubMed: 20603775]
- Endress AD, Potter MC. Something from nothing: Buildup of object memory from forgettable single fixations. [ms13_160]. *Atten Percept Psychophys*, [Epub ahead of print]. 2014
- Fougnie D, Marois R. What limits working memory capacity? Evidence for modality-specific sources to the simultaneous storage of visual and auditory arrays. *J Exp Psychol Learn Mem Cogn*. 2011; 37(6):1329–1341. [PubMed: 21859231]
- Gilchrist A, Cowan N. A two-stage search of visual working memory: investigating speed in the change-detection paradigm. *Attention, Perception, & Psychophysics*. 2014:1–20.
- Gilchrist AL, Cowan N. Can the focus of attention accommodate multiple, separate items? *J Exp Psychol Learn Mem Cogn*. 2011; 37(6):1484–1502. [PubMed: 21767065]
- Hollingworth A, Richard AM, Luck SJ. Understanding the function of visual short-term memory: transsaccadic memory, object correspondence, and gaze correction. *J Exp Psychol Gen*. 2008; 137(1):163–181. [PubMed: 18248135]
- Huff M, Meyerhoff H, Papenmeier F, Jahn G. Spatial updating of dynamic scenes: Tracking multiple invisible objects across viewpoint changes. *Attention, Perception, & Psychophysics*. 2010; 72(3): 628–636.
- Johnson J, Simmering V, Buss A. Beyond slots and resources: Grounding cognitive concepts in neural dynamics. *Attention, Perception, & Psychophysics*. 2014:1–25.
- Ko P, Duda B, Hussey E, Mason E, Molitor R, Woodman G, et al. Understanding age-related reductions in visual working memory capacity: Examining the stages of change detection. *Attention, Perception, & Psychophysics*. 2014:1–16.

- Konstantinou N, Beal E, King J-R, Lavie N. Working memory load and distraction: dissociable effects of visual maintenance and cognitive control. *Attention, Perception, & Psychophysics*. 2014:1–13.
- Kool W, Conway ARA, Turk-Browne NB. Sequential dynamics in visual short-term memory. *Atten Percept Psychophys*, ms13_198. 2014
- Kwak H-W, Egeth H. Consequences of allocating attention to locations and to other attributes. *Perception and Psychophysics*. 1992; 51(5):455–464. [PubMed: 1594435]
- Lavie N. Distracted and confused?: selective attention under load. *Trends Cogn Sci*. 2005; 9(2):75–82. [PubMed: 15668100]
- Lorenc E, Pratte M, Angeloni C, Tong F. Expertise for upright faces improves the precision but not the capacity of visual working memory. *Attention, Perception, & Psychophysics*. 2014:1–10.
- Luck SJ, Vogel EK. The capacity of visual working memory for features and conjunctions. *Nature*. 1997 Nov; 390(20):279–281. [PubMed: 9384378]
- Luck SJ, Vogel EK. Visual working memory capacity: from psychophysics and neurobiology to individual differences. *Trends in Cognitive Sciences*. 2013; 17(8):391–400. [PubMed: 23850263]
- Mack, A.; Rock, I. *Inattentional Blindness*. Cambridge, MA: MIT Press; 1998.
- Magnussen S, Dyrnes S. High-fidelity perceptual long-term memory. *Psychological Science*. 1994; 5(2):99–102.
- Mall J, Morey C, Wolff M, Lehnert F. Visual selective attention is equally functional for individuals with low and high working memory capacity: Evidence from accuracy and eye movements. *Attention, Perception, & Psychophysics*. 2014:1–17.
- Neider MB, Zelinsky GJ. Exploring set size effects in scenes: Identifying the objects of search. *Visual Cognition*. 2008; 16(1):1–10.
- Nissen, MJ. Accessing features and objects: Is location special?. In: Posner, MI.; Marin, OSM., editors. *Attention and performance XI*. Hillsdale, NJ: Erlbaum; 1985. p. 205-219.
- Oberauer K, Hein L. Attention to information in working memory. *Current Directions in Psychological Science*. 2012; 21(3):164–169.
- Olivers CL, Schreij D. Visual memory performance for color depends on spatiotemporal context. *Attention, Perception, & Psychophysics*. 2014:1–12.
- Olivers CN, Peters J, Houtkamp R, Roelfsema PR. Different states in visual working memory: when it guides attention and when it does not. *Trends Cogn Sci*. 2011; 15(7):327–334. [PubMed: 21665518]
- Orhan AE, Jacobs R. Toward ecologically realistic theories in visual short-term memory research. *Attention, Perception, & Psychophysics*. 2014:1–13.
- Pan Y, Lin B, Zhao Y, Soto D. Working memory biasing of visual perception without awareness. *Attention, Perception, & Psychophysics*. 2013:1–12.
- Papenmeier F, Huff M. Viewpoint-dependent representation of contextual information in visual working memory. *Attention, Perception, & Psychophysics*. 2014; 76(3):663–668.
- Pertsov Y, Husain M. The privileged role of location in visual working memory. *Attention, Perception, & Psychophysics*. 2014; 76:1–11.
- Quak M, Pecher D, Zeelenberg R. Effects of motor congruence on visual working memory. *Attention, Perception, & Psychophysics*. 2014:1–8.
- Rajic J, Wilson DE. Asymmetrical Access to Color and Location in Visual Working Memory. *Atten Percept Psychophys*. 2014; 76:1–12.
- Rouder JN, Morey RD, Cowan N, Zwilling CE, Morey CC, Pratte MS. An assessment of fixed-capacity models of visual working memory. *Proc Natl Acad Sci U S A*. 2008; 105(16):5975–5979. [PubMed: 18420818]
- Salmela VR, Moisala M, Alho K. Working memory resources are shared across sensory modalities. *Attention, Perception, & Psychophysics*. 2014:1–13.
- Simons DJ, Rensink RA. Change blindness: past, present, and future. *Trends Cogn Sci*. 2005; 9(1):16–20. [PubMed: 15639436]
- Soto D, Hodsoll J, Rotshtein P, Humphreys GW. Automatic guidance of attention from working memory. *Trends Cogn Sci*. 2008; 12(9):342–348. [PubMed: 18693131]

- Soto D, Humphreys GW, Heinke D. Working memory can guide pop-out search. *Vision Res.* 2006; 46:1010–1018. [PubMed: 16257030]
- Souza A, Rerko L, Lin H-Y, Oberauer K. Focused attention improves working memory: implications for flexible-resource and discrete-capacity models. *Attention, Perception, & Psychophysics.* 2014:1–23.
- Suchow J, Fougner D, Brady T, Alvarez G. Terms of the debate on the format and structure of visual memory. *Attention, Perception, & Psychophysics.* 2014:1–9.
- Swan G, Wyble B. The binding pool: A model of shared neural resources for distinct items in visual working memory. *Attention, Perception, & Psychophysics.* 2014:1–22.
- Thornton TL, Gilden DL. Parallel and serial processes in visual search. *Psychol Rev.* 2007; 114(1):71–103. [PubMed: 17227182]
- Töllner T, Eschmann KJ, Rusch T, Müller H. Contralateral delay activity reveals dimension-based attentional orienting to locations in visual working memory. *Attention, Perception, & Psychophysics.* 2014; 76(3):655–662.
- Townsend JT, Wenger MJ. The serial-parallel dilemma: A case study in a linkage of theory and method. *Psychonomic Bulletin & Review.* 2004; 11(3):391–418. [PubMed: 15376788]
- Tsal Y, Lavie N. Attending to color and shape: The special role of location in selective visual processing. *Perception and Psychophysics.* 1988; 44:15–21. [PubMed: 3405725]
- Tsuchiya N, Koch C. Continuous flash suppression reduces negative afterimages. *Nat Neurosci.* 2005; 8(8):1096–1101. [PubMed: 15995700]
- van den Berg R, Ma W. Plateau-related summary statistics are uninformative for comparing working memory models. *Attention, Perception, & Psychophysics.* 2014:1–19.
- van Moorselaar D, Theeuwes J, Olivers CNL. In competition for the attentional template: Can multiple items within visual working memory guide attention? *Journal of Experimental Psychology: Human Perception and Performance.* 2014; 40(4):1450–1464. [PubMed: 24730738]
- Vogel EK, Machizawa MG. Neural activity predicts individual differences in visual working memory capacity. *Nature.* 2004; 428(6984):748–751. [PubMed: 15085132]
- Wilken P, Ma WJ. A detection theory account of change detection. *J Vis.* 2004; 4(12):1120–1135. [PubMed: 15669916]
- Wolfe JM. What do 1,000,000 trials tell us about visual search? *Psychological Science.* 1998; 9(1):33–39.
- Wolfe JM. Saved by a log: How do humans perform hybrid visual and memory search? *Psychol Sci.* 2012; 23(7):698–703. [PubMed: 22623508]
- Wolfe JM, Alvarez GA, Rosenholtz R, Kuzmova YI, Sherman AM. Visual search for arbitrary objects in real scenes. *Atten Percept Psychophys.* 2011; 73(6):1650–1671. [PubMed: 21671156]
- Wolfe JM, Reinecke A, Brawn P. Why don't we see changes? The role of attentional bottlenecks and limited visual memory. *Visual Cognition.* 2006; 19(4–8):749–780. [PubMed: 18974792]
- Xing Y, Ledgeway T, McGraw P, Schluppeck D. The influence of spatial pattern on visual short-term memory for contrast. *Attention, Perception, & Psychophysics.* 2014:1–8.
- Xu Y, Chun MM. Dissociable neural mechanisms supporting visual short-term memory for objects. *Nature.* 2006; 440(7080):91–95. [PubMed: 16382240]
- Yu CP, Samaras D, Zelinsky GJ. Modeling visual clutter perception using proto-object segmentation. *J Vis.* 2014; 14(7)
- Zhang W, Luck SJ. Discrete fixed-resolution representations in visual working memory. *Nature.* 2008; 453:233–235. [PubMed: 18385672]

Figure 1.
Two of the most popular methods for studying visual working memory.

Figure 2.
Publication rates for visual working memory papers and two comparable topics.