Resource Limitations in Visual Cognition

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Abstract

Visual attention and visual working memory are two of the core resources that support visual perception. Foundational research has demonstrated that these resources are highly limited, but an active debate concerns exactly how they are limited. While many classic studies suggested that these resources are fundamentally discrete, with fixed capacity of 3–4 objects maximum, a number of recent studies have argued that these resources are fundamentally continuous, with no fixed upper-bound to the number of objects that can be attended or remembered. This entry reviews the state of this debate, and shows how convergence between these (often separate) areas of research is a major emerging trend in the field of visual cognition.

INTRODUCTION

The visual system is constantly overwhelmed with information. As the amount of input registered in early vision far outstrips the capacity of more computationally expensive later stages of visual processing, it is impossible to fully process and perceive everything in view at any given moment. Additionally, because low-level visual input is frequently in flux (due to blinks, eye movements, and physical changes in the environment), the visual system has to solve tricky correspondence problems in order to maintain perceptual stability. To meet these challenges, vision relies on a pair of core resources: *visual attention*, which serves as a filter to ensure that only relevant objects are fully processed, and *visual working memory* (VWM), which supports perceptual stability by providing a temporary storage for recent visual input. Unfortunately, these resources are highly limited, and there are often limits to the number of objects that can be simultaneously attended or actively remembered. When these limits are exceeded, dramatic failures of visual awareness can occur (e.g., *inattentional blindness* and *change blindness*).

This entry will explore the nature of these visual resources and address the following questions along the way: How many objects can be attended or

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remembered at one time? Are these resources fundamentally discrete (with fixed precision) or continuous (with variable precision)? What explains these limits, and are they fixed, or are there ways to increase one's resources? While drawing novel connections between parallel work on visual attention and VWM, this essay will show that their convergence—both theoretical and methodological—represents a major emerging trend in visual cognition.

FOUNDATIONAL RESEARCH ON VISUAL WORKING MEMORY RESOURCES

VWM is a highly limited resource, as is clear from demonstrations of "change blindness" in which observers fail to detect dramatic changes occurring between glances of a scene (Rensink *et al.*, 1997; Simons & Levin, 1997; cf. Scott-Brown *et al.*, 2000, for an alternative discussion of how such effects may reflect "comparison blindness" rather than memory limitations). A simplified version of this *change detection* paradigm has become a common way to measure VWM. In one seminal study (Luck & Vogel, 1997), observers briefly viewed 1–12 objects that disappeared briefly and then reappeared, with a change occurring to a single object on some trials. Observers' performance at detecting these changes suggested that they could store the features of only ~4 objects per trial, confirming that VWM capacity is quite low. Intriguingly, observers were just as good at noticing changes to objects that had only one feature as to objects that could change along any of four feature dimensions, which led the authors to conclude that VWM is a fundamentally *discrete* resource constrained by the number of objects stored rather than their complexity. While subsequent studies challenged the strongest versions of this hypothesis (Wheeler & Treisman, 2002; Xu, 2002), the basic finding of an upper limit in VWM capacity of 3–4 fairly simple objects has been repeatedly verified (e.g., Awh *et al.*, 2007; Vogel *et al.*, 2001).

An influential study (Zhang & Luck, 2008) using a continuous report paradigm provides even more powerful evidence for discrete VWM resources. Observers briefly viewed 1–6 objects and then reported a test object's feature value from memory (e.g., color) by selecting it from a continuous circular distribution (e.g., a color wheel). When the data were fit to a *mixture model* with a normally-distributed component (reflecting trials in which the probed item was noisily encoded) and a uniform component (reflecting random guessing for unencoded items), they found that the uniform component sharply increased from set size 3–6 but that the standard deviation of the normally-distributed component (a measure of the precision of encoding) did not change. This suggests that once participants had fully allocated their ~3 fixed-capacity VWM "slots," they failed to encode any information from additional items and had to guess at random.

Precision also decreased from set size 1–3, which the authors explain in terms of a "Slots + Averaging" model: for set sizes under 3, participants allocate multiple slots (each containing some independent noise) to each item allowing them to improve their performance by averaging across multiple noisy representations. Critically, however; the Slots + Averaging cannot account for recent findings that the typical drop in precision from set size 1–2 is larger that would be predicted by averaging (Bays *et al.*, 2009) and that under some conditions there is no drop in precision in this range whatsoever (Bae & Flombaum, 2013).

Another source of evidence for discrete VWM resource limits comes from investigations of the contralateral delay activity (CDA), a putative electrophysiological index of the number of items stored in VWM that increases with memory load but reaches plateau at ~3 objects in typical observers (Anderson *et al.*, 2011; Vogel & Machizawa, 2004). Notably, the CDA also indexes set size in a multifocal attention task (as reviewed below; Drew & Vogel, 2008; Drew *et al.*, 2011), suggesting that it may reflect spatial selection rather than memory, *per se*. Also, if the CDA fundamentally reflects discrete memory "slots," then following the logic of Slots + Averaging, all slots should be used in parallel even at set sizes 1–2 to improve precision via averaging, implying that there should not be differences in the CDA at small versus large set sizes.

CUTTING-EDGE RESEARCH ON RESOURCE LIMITATIONS IN VISUAL WORKING MEMORY

One of the central debates in VWM research concerns whether VWM resources are constituted by discrete fixed-capacity "slots," or a flexible, *continuous* resource that can be variably allocated to any number of objects. Critically, continuous resource models predict tradeoffs between complexity and capacity, as complex objects are assumed to require more resources to encode. Strong evidence for such effects came from a study (Alvarez & Cavanagh, 2004) that tested VWM capacity using stimuli ranging from very simple color patches to highly complex objects, such as Chinese characters or multi-shade cubes. The authors used both a change-detection task to estimate memory capacity for these different stimulus types, and a separate speeded-search task to quantify the complexity of each stimulus type. They observed an almost perfect linear correlation between these measures, verifying that memory capacity was much lower for the most complex objects (e.g., only ~1.5 cubes could be stored per trial).

Other work has shown that it is possible to store more than four representations in VWM, albeit at low precision. Bays & Husain (2008) found that in a spatial memory task, VWM resources could be spread among up to at least six objects, and that at increased set sizes there was a concomitant decrease in precision that follows a power law, consistent with a continuous resource being spread ever more thinly. There is also evidence that different objects in a scene can receive differing amounts of memory resources, with numerous studies finding that some objects can be prioritized (via cueing) over others (Bays & Husain, 2008; Gorgoraptis *et al.*, 2011). Even in the absence of cues, memory precision seems to naturally vary between objects and across trials, consistent with continuous resources (Fougnie *et al.*, 2012).

The upper threshold of ~3–4 representations observed in classical VWM tasks may reflect a tendency to represent a subset of items in high resolution and a subset in low resolution, with these low resolution representations being treated incorrectly by many models as "guesses" rather than as low-precision "hits" (van den Berg *et al.*, 2012), though the question of whether participants ever truly guess at random (due to a complete failure to encode any detail from the target) is a matter of debate (cf. Fougnie *et al.*, 2012). Alternatively, VWM resources may be continuous—even while behavioral performance exhibits strict (and seemingly discrete) capacity limits—because VWM relies on a fundamentally discrete indexing resource (possibly attention) to link VWM representations to spatial locations (Xu & Chun, 2009). Even if observers can store more than four representations, they may be unable to accurately link all of these representations to items in the test display, causing them to make accurate responses to the wrong items (Bays *et al.*, 2009; Emrich & Ferber, 2012).

These results are also compatible with a recent perspective that suggests that the fundamental units of VWM are not objects, but rather *hierarchical feature bundles* that encompass both object-based advantages in storing individual features and higher-order regularities (e.g., spatial and featural) that emerge across collections of objects, and that can enhance VWM capacity via compression and summary statistics (Brady *et al.*, 2011). Thus, even if there is a capacity limit to the number of objects that can stored independently with great precision, the actual capacity of VWM may be much higher because higher-order regularities may be encoded across all objects in the scene.

The work reviewed thus far has focused on the capacity and nature of VWM resources. However, to truly explain why and how these resources are limited, it is critical to consider computational and neural models of VWM. For example, multi-object working memory can be implemented via local spatial interactions between neurons following a "Mexican Hat" formation in which inhibition is high near the peak of each representation's activation and falls off with increasing distance. Such interactions help keep neighboring representations separate, but also keep overall inhibition within the network low enough to allow multiple items to be represented in parallel. Given certain parameterizations of these interactions, such neural models mimic typical human VWM capacity limits in change-detection (Johnson *et al.*, 2008). Relatedly, a recent, biologically plausible model (Wei *et al.*, 2012) illustrates how modeling representations as "activity bumps" in a continuous pool of neurons with excitatory and inhibitory properties gives rise to properties typically associated with both discrete and continuous models of VWM.

Instead of conceptualizing VWM resources as having a fixed upper bound capacity, a similar recent proposal suggests that these resources are fundamentally unlimited, with observed limits in task performance arising from spatial competition between representations in *content maps* (Franconeri, 2013; Franconeri *et al.*, 2013). Content maps are extensions of functionally- and spatially-organized neural substrate, and representations occupy physical locations within these neural maps. Objects that are physically close in visual or feature space thus become represented in neighboring regions of visual cortex, and must therefore compete for the same pool of neural resources. Visual capacity limits are thus a byproduct of the physical limitations of neural real estate and the competitive interactions that emerge between representations in these maps. For example, many VWM errors can be accounted for as spatial mismatches between sample and test items (Bays *et al.*, 2009; Emrich & Ferber, 2012), and decreasing similarity in integral feature dimensions (e.g., color in a brightness memory task) increases precision in VWM (Bae & Flombaum, 2013), suggesting that representational capacity may be much higher than spatial indexing capacity.

Alternatively, VWM resource limitations may arise due to purely temporal properties of the neural substrates of memory. According to the principle of *oscillatory multiplexing*, memory representations are encoded in oscillating patterns of global brain activity. Lisman and Idiart (1995) suggest that a working memory capacity of 7 ± 1 could be derived from the number of high-frequency gamma (40 Hz) brain oscillations that fit within a single low-frequency alpha–theta (5–12 Hz) oscillation, though more recent formulations (Raffone & Wolters, 2001; Siegel *et al.*, 2009) have argued for values closer to the classic "slots" capacity of 4 ± 1 items. A major advantage of these theories is that they show how brains that are inherently continuous (having pools of billions of neurons) can nonetheless behave in a way that is discrete and slot-like. The downside is that there is very little direct empirical support for these theories thus far. Furthermore, while multiplexing theories are typically associated with discrete resource theories, they could also be consistent with continuous resources if variability in these oscillatory rates is causally related to memory precision. For example, different patterns of oscillation might result in higher capacity but lower precision because each representation receives a smaller temporal share of memory resources.

Of course, a computational model that can simulate characteristics of human performance via careful tweaking of free parameters is not especially compelling in and of itself. Thus, the challenge is to link such parameters to actual neural measures and individual differences in human behavioral performance (e.g., the amount and shape of "inhibition" observed between neighboring representations on some VWM task), and then use these parameters to predict individual differences in resource capacity.

FOUNDATIONAL RESEARCH ON RESOURCE LIMITATIONS IN VISUAL ATTENTION

When observers focus all of their attention on a challenging primary task, even highly salient changes (e.g., the sudden appearance of a gorilla) can go unnoticed (Mack & Rock, 1998; Simons & Chabris, 1999). This effect, called *inattentional blindness*, is thought to reflect the limited capacity of attention—when attention is "used up" by the primary task, there are insufficient resources to detect the salient changes. While such demonstrations reveal that attentional resources are limited, other measures focus on quantifying these limitations. In *multiple object tracking* (MOT), observers see a display filled with identical objects, some of which are cued as "targets." All objects then move independently (and often, unpredictably), and observers must keep track of the targets' positions throughout the movement and later reidentify them. These studies showed that people could track at least four objects (Pylyshyn & Storm, 1988; Yantis, 1992) suggesting an underlying capacity limit in the ability to divide attentional resources (Pylyshyn & Storm, 1988). This limit matched values obtained from broader literatures on memory (Cowan, 2001), leading some to suggest that VWM and visual attention rely (at least partially) upon a common pool of resources, with VWM being constrained by a form of "inward-directed" attention (Chun, 2011; Gazzaley & Nobre, 2012).

CUTTING-EDGE RESEARCH ON RESOURCE LIMITATIONS IN VISUAL ATTENTION

Mirroring the debate in the VWM literature over whether capacity reflects a fixed number of discrete object-based "slots" or a more continuous resource, new research on MOT explores similar divisions. Like VWM, the upper limit on capacity does not appear to be fixed—recent studies show that there are in fact display conditions where tracking capacity can be raised to eight objects at once (Alvarez & Franconeri, 2007). Like VWM, there are arguments that objects are represented not as individuals in "slots," but that higher-order structures (hierarchical features bundles for VWM, e.g., Brady *et al.*, 2011) might help compress position representations of objects. For example, there is evidence that tracked objects might be organized by common fate or as vertices of a rigid polygon (Yantis, 1992, see Scimeca & Franconeri, 2015, for discussion).

There are also several demonstrations of performance limits that appear to reflect continuous allocation of processing resources. For example, participants are capable of tracking up to eight objects at a time, but only when the objects move very slowly (Alvarez & Franconeri, 2007). Relatedly, at very fast speeds only a single object can be successfully tracked (Holcombe & Chen, 2012). These results may suggest a capacity-precision tradeoff in visual attention, with faster moving objects demanding additional resources, though such explanations are controversial (cf. Franconeri *et al.*, 2010).

Given how instrumental continuous report measures have been in recent studies of the nature of VWM resources, the development of continuous report measures in MOT may similarly inform debate over the nature of visual attention resources. For example, a recent study in which “targets” in a simplified tracking task disappeared at the end of each trial and then had to be localized from memory via mouseclicks found that with increasing tracking load, response clicks lagged increasingly far behind each target’s true position relative to its direction of motion (Howard & Holcombe, 2008), though these effects do not seem to generalize to more typical MOT displays (Howard *et al.*, 2011). Relatedly, Horowitz and Cohen (2010) asked participants to judge the last-remembered trajectory angle of targets at set sizes ranging from 1 to 6. When they fit these data to a two-component mixture model (as in Zhang & Luck, 2008) to derive separate estimates of the probability and precision of tracking, they found that angular error for targets increased continuously up to set size 6, consistent with a continuous resource.

There are also parallels to the proposed set of underlying mechanisms for limits in VWM, which can be divided into spatial (cortical map limitations) and temporal (oscillatory multiplexing) theories. Explanations of attention resources as spatially limited are supported by work demonstrating that target-distractor spacing influences tracking capacity. When spacing is maximized, observers can successfully track at least six objects in parallel, irrespective of object speed (Franconeri *et al.*, 2010; cf. Tombu & Seiffert, 2011), suggesting that attention may be a fundamentally continuous resource with no strict capacity limit. Critically, this proposal explains limits in tracking capacity as a consequence of competition within spatial attention maps (e.g., in the frontal eye fields and related parietal areas) arising during close interactions between targets and distractors, as such interactions involve destructive interference between representations. Relatedly, speed and spatial crowding may limit tracking performance by creating spatial confusability between targets and distractors (Franconeri *et al.*, 2010), analogous to how spatial confusions seem to reduce effective VWM capacity

(Bays *et al.*, 2009). In fast-moving displays, target objects have more frequent close interactions with distractors than in slow-moving displays, increasing the probability of selecting the wrong item, and thus, lowering capacity estimates.

Spatial content maps may also be partly interactive with feature-based content maps, such that objects that are similar along one dimension can be separately indexed (and successfully tracked or stored) so long as they are distinct along another dimension. This possibility is supported by recent work showing that tracking performance improves when targets and distractors are visually distinct during close encounters (Bae & Flombaum, 2012), suggesting that competition within one content map (e.g., spatial position) can be avoided or alleviated via distinctiveness within another (e.g., position in color space).

Support for a temporal basis for limitations of attention resources is provided by recent work claiming to show tradeoffs between capacity and the temporal precision of tracking. Holcombe and Chen (2013) show that a single target can be tracked at temporal resolutions up to 7 Hz (i.e., 0.58 rev/s on a clock face with 12 positions), but this threshold drops to 4 Hz for two targets and 2.6 Hz for three targets. This point is controversial, with some researchers arguing that these data do not reveal temporal resource limitations (Scimeca, Jonathan, & Franconeri, submitted). Also, as such effects could also be accommodated within a discrete-resource framework (via Slots + Averaging), a critical question is whether at even higher set sizes, temporal precision continues to decrease gradually, or whether temporal precision eventually bottoms out as guessing rate increases (as a discrete model would predict).

Another open question is whether attentional resources can be allocated unevenly during tracking, as appears possible for continuous VWM resources (Bays & Husain, 2008). While there is no solid evidence to date for such effects, a study design in which multiple targets per trial are probed with a continuous response (e.g., location or trajectory angle), or in which participants are asked to respond to the "best remembered" versus a randomly-chosen item (as in Fougnie *et al.*, 2012), or in which some targets are designated as "high-priority" and others as "low-priority" (perhaps reinforced by a monetary incentive structure), would be helpful in resolving this question.

It seems clear that attention researchers have much to gain by following developments in the study of VWM and vice versa. Even if visual attention and VWM involve distinct (though partially interactive) resources, both resources may be subject to similar architectural constraints. Also at stake is the question of whether attention and memory reflect the same resource, as such an account would require that attention and VWM resources are limited in the same way—either discretely or continuously.

CONCLUSIONS

While visual attention and VWM have often been studied as separate topics, using distinct methodologies (and, more often than not, by different groups of researchers), it seems clear that there is much to be gained from increasing theoretical and methodological convergence between these areas of research. For example, we have seen how major methodological advances in VWM research (e.g., continuous report paradigms and neural signatures such as the CDA) can inform fundamental theories of visual attention, in particular, the question of whether attention resources are fundamentally discrete or continuous, and of whether attention and VWM resources are the same or are distinct.

There are still many open questions left to resolve about the nature of these resources, but there is mounting evidence for continuous resource models in visual attention and VWM. If these resources truly are continuous, it will be crucial to understand why human performance sometimes appears to be discrete, and to synthesize this finding with neural measures (such as the CDA and global oscillatory activity) that are inherently discrete. More generally, a deeper understanding of resource limitations will require both continued advances in behavioral and neural measures of visual attention and VWM capacity and crosstalk between these fields. Eventually, visual cognition can begin to move beyond questions of how these resources are limited to more fundamental questions about what these resources are and how to maximize them in everyday contexts.

KEY ISSUES FOR FUTURE RESEARCH

1. How much overlap is there between visual attention and VWM resources? Do they have the same capacity? Are they both discrete or both continuous?
2. Is there such a thing as a true "guess" in VWM? Or are all objects in the scene always encoded with at least a minimal amount of resources?
3. Is there a true upper bound to the number of objects that can be remembered or tracked? Likewise, is there an upper bound to the resolution with which a single object can be tracked or remembered?
4. To what extent are objects encoded independently versus hierarchically in VWM and attention?
5. Can speed impair tracking performance independently of spacing?

6. Can visual attention resources be divided unevenly among objects, as VWM resources seemingly can be?
7. What is the ultimate neural basis of visual resources? Can individual differences in VWM and MOT performance be predicted based on differences in brain activity?

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