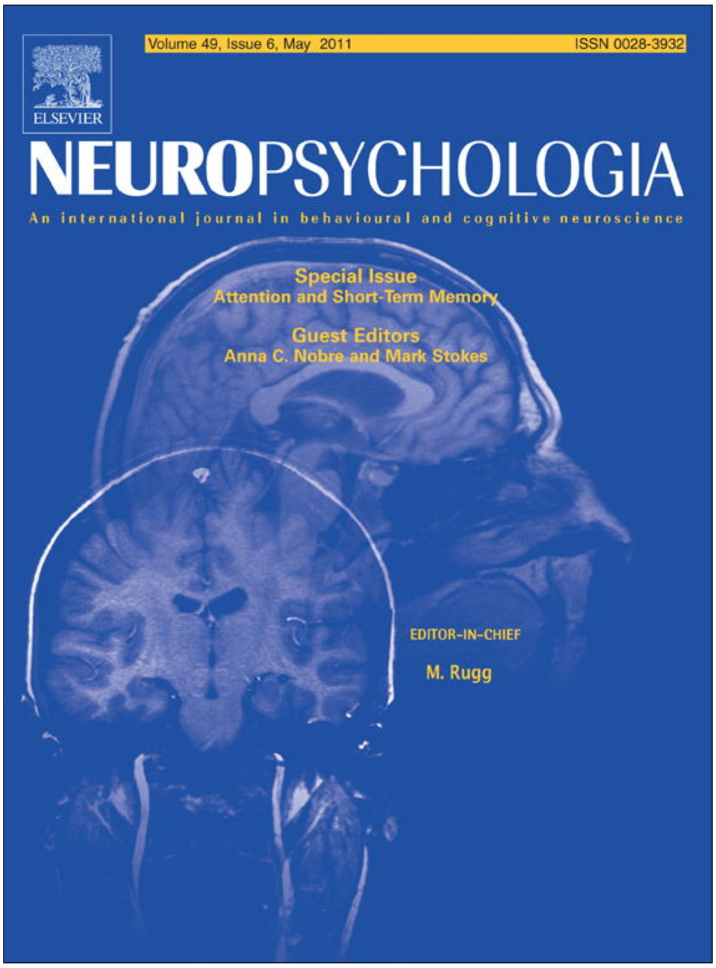
Volume 49, Issue 6, May 2011
ISSN 0028-3932
ELSEVIER
NEUROPSYCHOLOGIA
An international journal in behavioural and cognitive neuroscience
Special Issue
Attention and Short-Term Memory
Guest Editors
Anna C. Nobre and Mark Stokes
EDITOR-IN-CHIEF
M. Rugg

Neuropsychologia 49 (2011) 1401–1406

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

The focus of attention as observed in visual working memory tasks: Making sense of competing claims

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ARTICLE INFO

Article history:
Received 29 November 2010
Accepted 19 January 2011
Available online 26 January 2011

Keywords:
Capacity limits
Visual working memory
Multi-sensory working memory
Multi-modal working memory
Focus of attention

ABSTRACT

Recent behavioral and neuroscientific evidence speaks to the question of whether the human focus of attention is limited to a single item or can accommodate several items. This issue is fundamental to an understanding of the nature of human cognition and brain function. Here I review evidence from visual working memory tasks and suggest that it supports the concept of a focus of attention that can include several items at once as a core vehicle of working memory, regardless of the stimulus modality. One brain area in particular, the left intraparietal sulcus (IPS), seems critically important in the network underlying the focus of attention as a working memory storage mechanism. This view is reconciled with evidence previously taken to indicate that the focus of attention only includes a single item at a time, which is reinterpreted here.

1. Introduction

A research participant's focus of attention and the mechanisms underlying it comprise one of the most important and interesting areas in need of clarification by cognitive neuroscience. The focus of attention supposedly would reflect what is in conscious awareness, and measurements of its capacity might differ among individuals and age groups (Cowan, Elliott, et al., 2005; Cowan, Fristoe, Elliott, Brunner, & Saults, 2006; Cowan, Johnson, & Saults, 2005; Gold et al., 2006). Recently, there have been competing claims regarding the nature of the focus of attention as observed in visual working memory tasks. My intent is to evaluate those claims and consider how they might be reconciled. I will concentrate on tasks that have been used in both behavioral studies and neuroscientific (primarily neuroimaging) studies.

1.1. The data base

Claims about the focus of attention have been made using various types of methods, including some in which the key measurement is how quickly participants use information in memory to calculate new results (e.g., Oberauer, 2002, 2005). The following discussion, however, will focus on a simpler type of task that has been used in both behavioral and brain studies. In this type of task a set of items, presented in either a simultaneous array or a sequential list, is followed by a retention interval and then a single probe item to be judged present in the set or absent from it. What is most important is the change in performance as a function of the number of items in the set and, when items are presented sequentially, as a function of the serial position in the list. Behavioral data with such tasks have included reaction time for correct responses (e.g., Cowan, Elliott, et al., 2005; Cowan, Johnson, et al., 2005; Garavan, 1998) and the rate of increase in accuracy as a function of the available processing time (McElree & Dosher, 1989). With similar procedures, neuroimaging data have consisted of identification of brain areas sensitive to increases in set size of an array (e.g., Todd & Marois, 2004) and serial position within a list (e.g., Nee & Jonides, 2011; Öztekin, Davachi, & McElree, 2010). Competing claims have been made on the basis of this type of task, as follows.

2. Competing claims

The main competing claims to be considered are that there is evidence from visual working memory tasks in favor of (1) a multi-item focus of attention (e.g., Cowan, 1995, 1999, 2001, 2005), or (2) a single-item focus of attention (e.g., McElree, 1998; Öztekin et al., 2010). A second set of competing claims that will be mentioned in passing, but not highlighted in this review, are that there is clear evidence for a distinction between long-term memory and working memory (Cowan, 1995; Cowan, Nugent, Elliott, & Geer, 2000; Davelaar, Goshen-Gottstein, Ashkenazi, Haarman, & Usher, 2005; Nee & Jonides, 2011) or that there is no such evidence (Nairne, 2002; Öztekin et al., 2010).

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doi:10.1016/j.neuropsychologia.2011.01.035

2.1. Multi-item focus of attention

2.1.1. Evidence of a multi-item capacity limit

Cowan (1988, 1995, 1999) described the information processing system as one in which there are embedded processes: (1) the memory system; (2), within it, a portion of the system that is currently in a heightened state of activation; and (3) within that, a portion of the system that is currently in the focus of attention. Activated memory was said to include diverse features of stimuli and ongoing thoughts, including both physical and semantic features, limited only by decay over time and by interference. In contrast, the focus of attention was said to include coherent, integrated items (chunks; see Miller, 1956), and was said to be limited to 3–5 chunks. In a different, prominent approach in the field, a component called the *episodic buffer* is said to hold this integrated information but its attention requirements are not yet clear (Baddeley, 2000, 2001).

The capacity limit of the focus of attention is supposed to be directly observable provided that further grouping (Miller, 1956), rehearsal (Baddeley, 1986), or refreshing processes (Raye, Johnson, Mitchell, Greene, & Johnson, 2007) cannot be used to supplement the information, and provided that knowledge of the physical features of items to be remembered have been eliminated using subsequent masking stimuli (Cowan, 2001). This leaves a more semantic type of representation. The number of items in the focus of attention, according to this view, is estimated by the number in working memory when an array to be remembered is followed by a mask and then by a probe to be recognized (Saults & Cowan, 2007). The number can be estimated with formulas that take into account guessing (Cowan, 2001; Cowan & Rouder, 2009; Rouder et al., 2008), basically as follows.

2.1.1.1. Behavioral evidence of a capacity limit. In the field of visual working memory, much research has been based on a procedure derived from Luck and Vogel (1997). In a common version of this procedure, an array of items (or objects) on a computer screen, such as small squares of different colors, is followed by a single probe item that might be the same as the array item that had occupied that location on the screen, or might have changed (for example, to a different color). The number of items loaded into visual working memory has been evaluated with a simple formula derived by Cowan (2001), based on the notion that if k items are in memory and the probed item is one of those items, the participant will know the answer; otherwise, he or she will guess. For a stimulus set with N items, this leads to the formula, $k = N(hits\text{-}fa)$, where *hits* refers to the proportion of correct change detection out of all trials in which there was a change between the probed item and the probe, and *fa* refers false alarms, the proportion of trials with no change in which the participant incorrectly indicated that there was a change.

It seems clear that the limit on the number of items that can be temporarily retained from a visual array in working memory in this type of procedure is approximately constant within an individual, across variations in the complexity of the stimuli (Awh, Barton, & Vogel, 2007; Fukuda, Awh, & Vogel, 2010), the number of features in the stimuli (Luck & Vogel, 1997), and both the number of items in the array and the guessing bias (Cowan & Rouder, 2009; Rouder et al., 2008; Zhang & Luck, 2008). It is generally constant at $3 < \text{maximal } k < 4$ (e.g., Cowan, 2001). What has been less clear is what part of the memory system accounts for this constant capacity. There are reasons to believe it is the focus of attention, a point that will be explained below in Section 2.1.2.

2.1.1.2. Neuroscientific evidence of a capacity limit. Recent research has sharpened this limited-capacity concept on the basis of neuroimaging evidence, which points to the intraparietal sulcus (IPS) as especially important in multisensory attention (for a review see Cowan et al., 2011; for additional recent evidence see Anderson, Ferguson, Lopez-Larson, & Yurgelun-Todd, 2010). Todd and Marois (2004) tested probe recognition from arrays of various numbers of items and showed that the intraparietal sulcus (IPS) responded in a special way. Although many areas of the brain showed increased activation with increasing set size, only the IPS also showed leveling off of the brain activity when the capacity limit was reached. It leveled off at the same set size as the behavioral estimate k, the number of items in working memory (cf. Xu & Chun, 2006). Next we address the evidence that this capacity-limited storage is in fact the focus of attention.

2.1.2. Evidence that the capacity-limited storage mechanism is the focus of attention

2.1.2.1. Behavioral evidence of a capacity-limited focus. Some of the behavioral evidence has involved verbal lists rather than arrays of nonverbal items but, similar to the research with nonverbal arrays, has been based on the presentation of a single probe to be recognized as present in the list or absent from it. This research is modeled after Sternberg (1966) and the emphasis has been on reaction times in addition to proportion correct. The research has hinged on the concept of proactive interference (PI), the tendency for stimuli from a previous trial to interfere with memory for an item on the current trial that resembles the previous stimuli. This interference should occur while an individual is trying to retrieve an item from memory. Assuming that items in the focus of attention are in an important sense already retrieved, they should not encounter the same kind of PI. A few studies have found that both phonological PI and semantic PI occur much less in the recognition of probes for lists of 4 or fewer items than for lists of 5 or more items (e.g., Cowan, Elliott, et al., 2005; Cowan, Johnson, et al., 2005; Halford, Maybery, & Bain, 1988). The implication is that up to 4 items are in the focus of attention.

Another line of evidence examines the possibility that working memory for visual arrays requires attention during a maintenance period imposed between the arrays and the probe. If so, there should be interference from attention-demanding distractions even when they share few features with the array to be remembered. In fact, probe recognition for nonverbal visual arrays is impaired by distraction during the maintenance period, which has included such diverse distracting stimuli as overt rehearsal of 7 random digits, which affect performance even though a known 7-digit number does not (Morey & Cowan, 2004); tone identification (Stevanovski & Jolicoeur, 2007); and retrieval of verbal items from a learned list, even if that retrieval does not require overt responding (Ricker, Cowan, & Morey, 2010). There is a tradeoff between working memory for a visual array versus a tone sequence when the payoffs favoring retention of one task versus the other are varied (Morey, Cowan, Morey, & Rouder, 2011). There is also an attention conflict between verbal lists to be remembered and a nonverbal choice reaction time task (Chen & Cowan, 2009).

Most important for the notion of a capacity-limited focus of attention is a demonstration of a fixed capacity across different codes and modalities, under the right circumstances. Saults and Cowan (2007) found that working memory in adults could include about 4 visual items or, when attention was split between a visual array and an array of spoken digits from 4 loudspeakers, about 4 items total: typically in this task, 3 visual items plus 1 spoken digit (Saults & Cowan, 2007).

The constant-capacity result of Saults and Cowan (2007) was obtained across 3 experiments that included a post-stimulus mask in both modalities to eliminate the contribution of sensory memory. (It was not obtained in 2 other experiments without the mask.) In one experiment leading to a constant capacity, the visual-nonverbal and auditory-verbal stimuli were presented at different times rather than concurrently, and the constant-capacity result was still obtained. In another such experiment, the spatial arrangement of the spoken digits was irrelevant and all that was relevant in that modality was the association between digit identities and the voice quality in which each was spoken; yet the 4-item limit across modalities held up.

The cross-modality findings suggest that there may not be a separate module for visual working memory, but rather a general mechanism holding a certain number of meaningful units originating in any modality. Given that attention can influence the contents of this general, limited-capacity storage mechanism, it is quite reasonable to believe that the storage mechanism may be the focus of attention itself and that what the participant is attending to is the representations of the several items in focus.

2.1.2.2. Neuroscientific evidence of a capacity-limited focus. The idea that the human parietal lobes of the brain form a critical part of the seat or focus of attention was first based on evidence from brain lesions (for a review see Cowan, 1995) and can be traced back at least to Luria (1966). Recent evidence supports and further clarifies that idea. For example, Cowan et al. (2011) examined whether there existed an area of the brain that responds to a 4-item load more than a 2-item load regardless of the stimulus codes and modalities. Two types of 2-item loads were used (2 colored squares or 2 spoken digits) and two types of 4-item loads were used (4 colored squares, or 2 colored squares plus 2 spoken digits). There was one area that showed a significant load effect for any of the 4-versus 2-item contrasts: the left IPS. Given that this same area responds in a capacity-limited manner to visual items (Todd & Marois, 2004), it appears likely that it actually includes items represented elsewhere in the brain multi-modally, rather than just visually (or, stated more precisely, it points to or indexes these items' representations that exist elsewhere in the brain).

Some recent studies reviewed by Cowan et al. (2011) suggest that the left IPS also is a hub of functional connectivity that is active regardless of the nature of the stimuli in a working memory task, with the specific types of stimuli determining which other areas are active (e.g., Hamidi, Slagter, Tononi, & Postle, 2009; Majerus et al., 2010; Palva, Monto, Kulashekhar, & Palva, 2010). Other recent studies reviewed by Cowan et al. suggest that the left IPS also is involved in spatial attention to objects that are present in the field rather than just in working memory, again with a similar, related capacity limit (e.g., Mitchell & Cusack, 2008; Silk, Bellgrove, Wrafter, Mattingley, & Cunnington, 2010). These findings together suggest that the left IPS may be a critical part of the neural circuit that reflects the focus of attention, and that this focus of attention can include several items that were presented recently and are no longer present; i.e., that it can function as a capacity-limited working memory store.

This point is not meant to rule out the possibility that other areas also are involved in working memory. As Todd and Marois (2004) showed, for example, prefrontal cortical areas also respond to a memory load, but apparently do not reach an asymptote in activity level like the IPS does as the behaviorally-observed capacity limit is approached and then exceeded. Prefrontal areas may be involved in processes that help maintain items in working memory, such as attentional refreshing (Raye et al., 2007). These processes may indeed be increasingly active as a function of set size, even past the capacity limit, though to no avail in terms of behavior after the capacity limit is reached.

2.2. Single-item focus of attention

There is another line of evidence that at first blush appears to be in direct conflict with the multi-item focus of attention described above.

2.2.1. Behavioral evidence of a single-item focus of attention

McElree and Dosher (1989) showed that there is a special status of the last item in a list. When the probe is identical to the last item, the memory is retrieved faster than for other items in the list. That is, the proportion correct increases across the available processing time more quickly than for other list items, which do not differ. The available processing time is manipulated by presenting a post-list tone after a variable period indicating that the participant should respond quickly; as that period increases, performance improves until it reaches an asymptote, and a parameter indicating the rate of improvement can be estimated. The retrieval dynamic was faster for the last item than for the other list items, which did not differ, and the theoretical proposal thus was that this last item is the only one in the focus of attention.

In one study (McElree, 1998), 9-item lists were presented with sequences of 3 consecutive items in the same semantic category (e.g., *desk*, *chair*, *lamp*, *shirt*, *hat*, *shoe*, *bird*, *dog*, *goat*). Then the accelerated retrieval dynamic was obtained for the last three words in the list. The interpretation was that the triplets from a semantic category are combined to form a single chunk, so it was still proposed that no more than a single chunk can occupy the focus of attention at one time.

2.2.2. Neuroscientific evidence of a single-item focus of attention

Öztekin et al. (2010) examined brain activation as a function of the serial position in the list. The activation of the hippocampal areas was said to be considerably lower for the last item in the list than for the previous items. The logic to interpret this result was similar to the logic for the behavioral study of PI. Specifically, information that is already in the focus of attention should not need to be retrieved and therefore should not require special hippocampal activity. By this logic, only the last list item was said to be in the focus of attention, in agreement with McElree and Dosher (1989).

Nee and Jonides (2011) replicated and extended this finding. They found unique types of brain activity that were most active for the second and third list items, said to reflect activated portions of long-term memory; for the fourth and fifth items, said to reflect a capacity-limited region outside of the focus of attention; and for the final, sixth item, said to reflect the focus of attention. In this regard, the theory of working memory was most like that of Oberauer (2002). Consistent with Öztekin et al. (2010), though, the hippocampus was most active for the items said to be in the capacity-limited region outside of the focus of attention.

3. Weighing the competing claims

3.1. Criticisms of the multi-item focus hypothesis

3.1.1. Critiquing the behavioral evidence

The evidence is strong in favor of a form of working memory that is of limited capacity, whether it is strictly visual in nature or more abstract as the multimodal data suggest (e.g., Saults & Cowan, 2007). What is less clear, though, is whether that form of working memory is the focus of attention (Cowan, 2001) or whether it is some sort of fringe surrounding that focus.

We know that what is kept in the capacity-limited form of memory depends on attention even during the maintenance period (Cowan & Morey, 2007; Saults & Cowan, 2007). However, it is theoretically possible that what is attention-demanding is not storage itself but, rather, a refreshing mechanism that cycles from one item to the next, refreshing the items in the capacity-limited region. That type of mechanism of attention would be consistent with the finding that memory span for lists separated by inter-item distracting stimuli varies as a linear function of the cognitive load. The cognitive load is defined as the proportion of time that is taken up by distraction and therefore is free to refresh the memoranda, counteracting decay of the memory's activation (Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007; Barrouillet, Portrat, & Camos, in press). This type of attention mechanism also is consistent with the finding in mice that two items in working memory produce two distinct patterns in the brain, active one after another in a rapidly-repeating cycle (Siegel, Warden, & Miller, 2009).

Theoretically, then, the capacity limit could emerge from a single-item focus cycling from one item to the next, within a set of up to about 4 items. If this is the case, then in principle it conforms to the theory of Oberauer (2002), which includes the activated portion of long-term memory, within it a capacity-limited region and, within that, a single-item focus of attention.

3.1.2. Critiquing the neuroscientific evidence

Neurally, a multi-item focus of attention might not be needed to account for multi-item storage. Oberauer's (2002) model that includes a single-item focus of attention along with a storage mechanism limited to several items, outside of the focus of attention, could be realistically implemented with a system in which the focus of attention, perhaps frontally represented in that model, could retrieve items from various cortical representations one at a time and help to put them in the capacity-limited region of working memory, by constructing and maintaining pointers in the IPS. Similarly, the episodic buffer (Baddeley, 2000, 2001) could be limited to several items from various sources and could be maintained with the help of attention without the items actually being in the focus of attention at the same time. Nevertheless, this type of model conflicts with one in which the single-item focus remains on one item while the several items in a capacity-limited region apparently persist without constant refreshing from attention being needed.

3.2. Criticisms of the single-item focus hypothesis

3.2.1. Critiquing the behavioral evidence

The first point to be made is that a single-item focus that consistently represents the final item in a list, as proposed by McElree and Dosher (1989), cannot also account for a capacity limit of up to about 4 items. To do so, the focus would have to circulate among the 4 or so items and therefore could not remain consistently on the final list item. The faster retrieval dynamic of the final item in the list compared to the other items (McElree & Dosher, 1989) could occur for reasons that have little to do with attention. It could reflect the absence of retroactive interference for that item, for example.

The especially fast retrieval dynamic of the last list item does not necessarily constitute evidence of an attention-related component of memory. An attention-related component should be flexibly allocated to one item or another voluntarily, and it has not been shown that attention can be removed from the final list item to accrue for a different item. In contrast, the 4-item limit does display that property because, as noted above, the limited-capacity system can be filled with some items at the expense of others, depending on instructions (e.g., Morey et al., 2011; Saults & Cowan, 2007), and the priorities of items in working memory can be altered even after the stimulus presentation by retroactive cues (Cowan et al., 2011, Experiment 1; Griffin & Nobre, 2003; Makovski, Sussman, & Jiang, 2008).

One can further question McElree's (1998) interpretation of the finding that items from the last category of a categorized list, including the 3 items from the final category, show the fast retrieval dynamic. The probe often was another item from the same category used as a lure, so it is unlikely that the category could be remembered as a single chunk (Cowan, 2001; Miller, 1956), as opposed to a more weakly associated triplet of items from the same category. If the three items became a true single chunk then memory for the three items in the category should be recalled at identical levels whereas, instead, a scalloped shape was obtained in memory performance for that last triplet of items. The three items from a category are probably associated, but not to the point that memory for one item inevitably invokes memory for another. Instead, it could reflect the capability of the system of holding at least 3 items from a category in the focus of attention.

3.2.2. Critiquing the neuroscientific evidence

Clearly the final item in a list is special, but it does not seem as special as the proponents of the single-item focus view have maintained. The actual data of Öztekin et al. (2010) shows lowered hippocampal activity not only for the final item, but also to some extent for the first list item, even though that point is not noted in the discussion. Its Fig. 4 actually shows even less activity of the left hippocampus for the first item in the list than for the last item, a striking discrepancy from their theoretical model. It seems relevant that the primacy effect, or excellent recall of the early list items, can be accounted for by the recency of the last rehearsal of those items (Tan & Ward, 2000). So at least two items seem to be conferred a special status.

Although Öztekin et al. (2010) proposed that there is no evidence at all in their 12-item lists for a capacity-limited region other than the single-item focus of attention, their data actually suggest otherwise. There was an area of the brain that was more active for Serial Positions 9–11, defined as the potential active set (Oberauer's capacity-limited region and Cowan's focus of attention), than for Serial Positions 1–8 (Cowan's and Oberauer's activated portion of long-term memory). The area was the supramarginal gyrus, which is part of Brodmann's Area 40. The IPS region observed for abstract working memory storage by Cowan et al. (2011) was rather close to that area, so the story that can be told is fairly consistent. Note that the basis of this consistency is unlikely to be that the memory of visual stimuli is recoded verbally, given precautions that have been taken. For example, Cowan et al. (2011) (Experiment 2) used articulatory suppression to prevent verbal rehearsal.

The question then becomes which, if any, of the components examined by Öztekin et al. (2010) reflects the focus of attention. Their interpretation was that the hippocampus indicates retrieval from memory; consequently they suggested that the item with little hippocampal activity at retrieval, the last item, required no retrieval and therefore must have been in the focus of attention. However, it is not clear that we have a good understanding of everything that the hippocampus does. It has sometimes been proposed that the hippocampus serves to bind items to their context, even in working memory (e.g., Baddeley, Allen, & Vargha-Khadem, 2010; Moses & Ryan, 2006). The serial position context of the first and last list items may be easier to retain than the context of medial list items, given that these items occur at the edges of the list. This could account for the lower hippocampal activity of these items. In contrast, as noted above, the parietal regions seem intricately involved in the focus of attention, and Öztekin et al. did find a difference between earlier and later list items in activation of a parietal region, with more neural activation for the items assumed to be more active in working memory (cf. Nee & Jonides, 2011).

3.3. Summary and conclusions

Behavioral and neuroscientific evidence has been summarized, some favoring the existence of a single-item focus of attention and some favoring a multi-item focus of attention with a limit of about 3 or 4 items in normal adults.

The last item of a list is special in some way, though the first item also appears special in a similar way. Both of them result in less hippocampal activity than medial list items. The last item also results in faster retrieval dynamics than the other items. However, there is no evidence of voluntary allocation of attention or tradeoffs between stimuli under different task instructions that would suggest that this special status reflects the focus of attention, despite the conclusion of McElree (1998) and Öztekin et al. (2010).

In contrast, there does appear to be an area of the brain that is related to the focus of attention, the left IPS (though, of course, it seems likely that this region works in close conjunction with other brain areas). This brain area shows a capacity limit of 3 or 4 items, in conformity with the behavioral data in the case of visual arrays (Todd & Marois, 2004), with convergent evidence on the role of the left IPS for verbal lists (Majerus et al., 2010) and combinations of visual arrays and acoustic-verbal lists (Cowan et al., 2011). The present view, therefore, is in favor of a focus of attention that holds several items, no matter whether their origin is visual or non-visual.

A final key point is that the time scale in question is important. What looks to be concurrent retention of several items in the focus of attention on a time scale of seconds might look like a rotation of activation between several items, like a quickly shifting flashlight beam, on a time scale of tens of milliseconds (Lisman & Idiart, 1995; Siegel et al., 2009). In that sense, both the single-item focus and the multi-item focus could be apt descriptions of the same phenomena on different time scales. Still, that rapidly rotating, single-item focus, allowing several items to be for all practical purposes in focus at once, would look very different from the single-item focus glued to one serial position in a list as in the conception of Nee and Jonides (2011) or Öztekin et al. (2010).

Acknowledgment

This work was supported by NIH grant R01-HD21338.

References

Anderson, J. S., Ferguson, M. A., Lopez-Larson, M., & Yurgelun-Todd, D. (2010). Topographic maps of multisensory attention. *Proceedings of the National Academy of Science of the United States of America*, *107*, 20110–20114.

Awh, E., Barton, B., & Vogel, E. K. (2007). Visual working memory represents a fixed number of items regardless of complexity. *Psychological Science*, *18*, 622–628.

Baddeley, A. (1986). *Working memory*. Oxford, UK: Clarendon Press.

Baddeley, A. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences*, *4*, 417–423.

Baddeley, A. (2001). The magic number and the episodic buffer. *Behavioral and Brain Sciences*, *24*, 117–118.

Baddeley, A., Allen, R., & Vargha-Khadem, F. (2010). Is the hippocampus necessary for visual and verbal binding in working memory? *Neuropsychologia*, *48*, 1089–1095.

Barrouillet, P., Bernardin, S., Portrat, S., Vergauwe, E., & Camos, V. (2007). Time and cognitive load in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *33*, 570–585.

Barrouillet, P., Portrat, S., & Camos, V. On the law relating processing to storage in working memory. Psychological Review, in press.

Chen, Z., & Cowan, N. (2009). How verbal memory loads consume attention. *Memory and Cognition*, *37*, 829–836.

Cowan, N. (1988). Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information processing system. *Psychological Bulletin*, *104*, 163–191.

Cowan, N. (1995). *Attention and memory: An integrated framework. Oxford Psychology Series No. 26*. New York: Oxford University Press.

Cowan, N. (1999). An embedded-processes model of working memory. In A. Miyake, & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 62–101). Cambridge, U.K.: Cambridge University Press.

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

Cowan, N. (2005). *Working memory capacity*. Hove, East Sussex, UK: Psychology Press.

Cowan, N., Elliott, E. M., Saults, J. S., Morey, C. C., Mattox, S., Hismjatullina, A., et al. (2005). On the capacity of attention: Its estimation and its role in working memory and cognitive aptitudes. *Cognitive Psychology*, *51*, 42–100.

Cowan, N., Fristoe, N. M., Elliott, E. M., Brunner, R. P., & Saults, J. S. (2006). Scope of attention, control of attention, and intelligence in children and adults. *Memory and Cognition*, *34*, 1754–1768.

Cowan, N., Johnson, T. D., & Saults, J. S. (2005). Capacity limits in list item recognition: Evidence from proactive interference. *Memory*, *13*, 293–299.

Cowan, N., Li, D., Moffitt, A., Becker, T. M., Martin, E. A., Saults, J. S., & Christ, S. E. A neural region of abstract working memory. Journal of Cognitive Neuroscience, 2011 Jan 24. [Epub ahead of print], doi:10.1162/jocn.2011.21625.

Cowan, N., & Morey, C. C. (2007). How can dual-task working memory retention limits be investigated? *Psychological Science*, *18*, 686–688.

Cowan, N., Nugent, L. D., Elliott, E. M., & Geer, T. (2000). Is there a temporal basis of the word length effect? A response to service (1998). *Quarterly Journal of Experimental Psychology*, *53A*, 647–660.

Cowan, N., & Rouder, J. N. (2009). Comment on "Dynamic shifts of limited working memory resources in human vision". *Science*, *323*(5916), 877.

Davelaar, E. J., Goshen-Gottstein, Y., Ashkenazi, A., Haarman, H. J., & Usher, M. (2005). The demise of short-term memory revisited: Empirical and computational investigations of recency effects. *Psychological Review*, *112*, 3–42.

Fukuda, K., Awh, E., & Vogel, E. K. (2010). Discrete capacity limits in visual working memory. *Current Opinion in Neurobiology*, *20*, 177–182.

Garavan, H. (1998). Serial attention within working memory. *Memory and Cognition*, *26*, 263–276.

Gold, J. M., Fuller, R. L., Robinson, B. M., McMahon, R. P., Braun, E. L., & Luck, S. J. (2006). Intact attentional control of working memory encoding in schizophrenia. *Journal of Abnormal Psychology*, *115*, 658–673.

Griffin, I. C., & Nobre, A. C. (2003). Orientational attention to locations in internal representations. *Journal of Cognitive Neuroscience*, *15*, 1176–1194.

Halford, G. S., Maybery, M. T., & Bain, J. D. (1988). Set-size effects in primary memory: An age-related capacity limitation? *Memory and Cognition*, *16*, 480–487.

Hamidi, M., Slagter, H. A., Tononi, G., & Postle, B. R. (2009). Repetitive transcranial magnetic stimulation affects behavior by biasing endogenous cortical oscillations. *Frontiers in Integrative Neuroscience*, *3*, 1–12. doi:10.3389/neuro.07.014.2009

Lisman, J. E., & Idiart, M. A. P. (1995). Storage of 7 + 2 short-term memories in oscillatory subcycles. *Science*, *267*, 1512–1515.

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

Luria, A. R. (1966). *The higher cortical functions in man*. New York: Basic Books.

Majerus, S., D'Argembeau, A., Martinez Perez, T., Belayachi, S., Van der Linden, M., Collette, F., et al. (2010). The commonality of neural networks for verbal and visual short-term memory. *Journal of Cognitive Neuroscience*, *22*, 2570–2593.

Makovski, T., Sussman, R., & Jiang, Y. V. (2008). Orienting attention in visual working memory reduces interference from memory probes. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *34*, 369–380.

McElree, B. (1998). Attended and non-attended states in working memory: Accessing categorized structures. *Journal of Memory and Language*, *38*, 225–252.

McElree, B., & Dosher, B. A. (1989). Serial position and set size in short-term memory: The time course of recognition. *Journal of Experimental Psychology: General*, *118*, 346–373.

Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, *63*, 81–97.

Mitchell, D. J., & Cusack, R. (2008). Flexible, capacity-limited activity of posterior parietal cortex in perceptual as well as visual short-term memory tasks. *Cerebral Cortex*, *18*, 1788–1798.

Morey, C. C., & Cowan, N. (2004). When visual and verbal memories compete: Evidence of cross-domain limits in working memory. *Psychonomic Bulletin and Review*, *11*, 296–301.

Morey, C. C., Cowan, N., Morey, R. D., & Rouder, J. N. Flexible attention allocation to visual and auditory working memory tasks: Manipulating reward induces a tradeoff. Attention, Perception, and Psychophysics, Epub ahead of print 2010, doi:10.3758/s13414-010-0031-4.

Moses, S. N., & Ryan, J. D. (2006). A comparison and evaluation of the predictions of relational and a conjunctive accounts of hippocampal function. *Hippocampus*, *16*, 43–65.

Nairne, J. S. (2002). Remembering over the short-term: The case against the standard model. *Annual Review of Psychology*, *53*, 53–81.

Nee, D. E., & Jonides, J. (2011). Dissociable contributions of prefrontal cortex and the hippocampus to short-term memory: Evidence for a 3-state model of memory. *Neuroimage*, *54*, 1540–1548.

Oberauer, K. (2002). Access to information in working memory: Exploring the focus of attention. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *28*, 411–421.

Oberauer, K. (2005). Control of the contents of working memory—A comparison of two paradigms and two age groups. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *31*, 714–728.

Öztekin, I., Davachi, L., & McElree, B. (2010). Are representations in working memory distinct from representations in long-term memory? Neural evidence in support of a single store. *Psychological Science*, doi:10.1177/0956797610376651

Palva, J. M., Monto, S., Kulashekhar, S., & Palva, S. (2010). Neuronal synchrony reveals working memory networks and predicts individual memory capacity. *Proceedings of the National Academy of Science of the United States of America*, *107*, 7580–7585.

Raye, C. L., Johnson, M. K., Mitchell, K. J., Greene, E. J., & Johnson, M. R. (2007). Refreshing: A minimal executive function. *Cortex*, *43*, 135–145.

Ricker, T. J., Cowan, N., & Morey, C. C. (2010). Visual working memory is disrupted by covert verbal retrieval. *Psychonomic Bulletin and Review*, *17*, 516–521.

Rouder, J. N., Morey, R. D., Cowan, N., Zwilling, C. E., Morey, C. C., & Pratte, M. S. (2008). An assessment of fixed-capacity models of visual working memory. *Proceedings of the National Academy of Sciences of the United States of America*, *105*, 5975–5979.

Saults, J. S., & Cowan, N. (2007). A central capacity limit to the simultaneous storage of visual and auditory arrays in working memory. *Journal of Experimental Psychology: General*, *136*, 663–684.

Siegel, M., Warden, M. R., & Miller, E. K. (2009). Phase-dependent neuronal coding of objects in short-term memory. *Proceedings of the National Academy of Science of the United States of America*, *15*, 21341–21346.

Silk, T. J., Bellgrove, M. A., Wrafter, P., Mattingley, J. B., & Cunnington, R. (2010). Spatial working memory and spatial attention rely on common neural processes in the intraparietal sulcus. *Neuroimage*, *53*, 718–724.

Sternberg, S. (1966). High-speed scanning in human memory. *Science*, *153*, 652–654.

Stevanovski, B., & Jolicoeur, P. (2007). Visual short-term memory: Central capacity limitations in short-term consolidation. *Visual Cognition*, *15*, 532–563.

Tan, L., & Ward, G. (2000). A recency-based account of the primacy effect in free recall. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *26*, 1589–1625.

Todd, J. J., & Marois, R. (2004). Capacity limit of visual short-term memory in human posterior parietal cortex. *Nature*, *428*, 751–754.

Xu, Y., & Chun, M. M. (2006). Dissociable neural mechanisms supporting visual short-term memory for objects. *Nature*, *440*, 91–95.

Zhang, W., & Luck, S. J. (2008). Discrete fixed-resolution representations in visual working memory. *Nature*, *453*, 233–235.