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Interactions between visual working memory and visual attention

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1. ABSTRACT

Visual attention is the collection of mechanisms by which relevant visual information is selected, and irrelevant visual information is ignored. Visual working memory is the mechanism by which relevant visual information is retained, and irrelevant information is suppressed. In addition to this overlap in definition, a strong overlap in brain areas active during attention and working memory tasks is found. The present paper reviews the behavioral evidence for and against the hypothesis that visual working memory and attention are best regarded as one and the same cognitive function, with the same capacity, the same control processes, and the same representational content. The data are best explained by a unified model in which multiple representations can be maintained, but only one receives the current focus of attention. Task circumstances then determine how successful this central representation can be prioritized over its mnemonic competitors.

2. INTRODUCTION

2.1. Visual attention and working memory are both selective

Imagine you are re-decorating your house. In front of the color charts in the Do-It-Yourself store, you are trying to imagine which paint would go nicely with the new sofa you just bought. This activity involves two of the most fundamental cognitive processes: visual attention and visual working memory. Visual attention is the mechanism by which we *select* relevant, and ignore irrelevant, visual information for a task. For example, you might be looking at different shades of blue, while ignoring yellow. Visual working memory is the mechanism by which we actively *retain* relevant, and prevent interference from irrelevant, visual information for a task. For example, you might close your eyes and try to actively imagine whether the blue you just looked at matches with the blue of the sofa back home. Despite this large overlap in definition, scientists have,

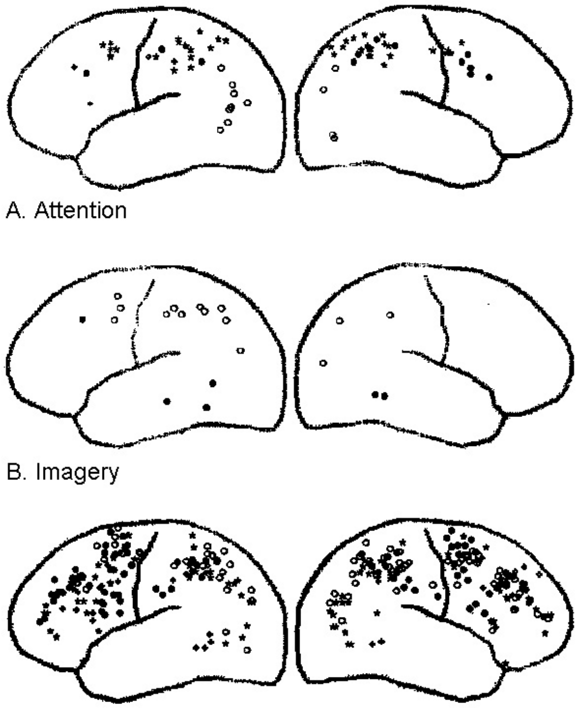

Figure 1. Lateral views of the left and right hemispheres demonstrating the large overlap in areas of activation associated with A) attention, B) imagery, and C) working memory tasks. Adapted with permission from ref. 4 (MIT Press).

until recently, largely treated visual selective attention and visual working memory as separate cognitive functions – each heavily grounded in their own literature. Theories of the one function often treated the other as given, or did not treat the other at all (1, 2). It is probably safe to say that the advent of neurophysiological and -imaging techniques during the 1990s changed all this.

2.2. Evidence from brain physiology

As has been extensively reviewed elsewhere (3-10), there is a striking overlap in brain areas active during attention and working memory tasks, as measured through fMRI, PET, single cell recordings, and selective lesion. Figure 1 illustrates this. In the frontal cortex, common regions include Brodmann areas 6 and 8 (supplementary motor area and frontal eye fields), areas 9, 44, and 46 (lateral prefrontal cortex), as well as area 32 (anterior cingulate). In the posterior brain, both types of tasks commonly activate Brodmann areas 7 and 40 (superior and inferior parietal cortex, respectively), and even occipital areas 18 and 19. This large overlap in brain areas involved in attention and working memory at the very least suggests strong reciprocal links between the two functions. Indeed, it prompts the hypothesis that the two concepts may reflect one and the same cognitive function, working on the same type of representations. In general terms, both attention and working memory processes selectively activate and prioritize particular representations above others – it is just that in the case of working memory, this occurs in the absence of the actual stimulus. More specifically, it has been proposed that the prefrontal cortex carries three distinct tasks: Working memory, preparatory task set, and inhibitory control (7). Functionally, these tasks closely correspond to the similar attentional concepts of attentional capacity, attentional set, and inhibition. To what extent then are these two psychological constructs indeed one and the same?

3. SHARED CAPACITY AND CONTROL PROCESSES

3.1. Shared capacity: A magical number four?

There are now several lines of evidence suggesting that visual working memory capacity is limited to about four units (or chunks). It would go too far to review all the evidence for this (11), and we confine ourselves to briefly mentioning the support for a "magical number four" in the visual modality. First, the number of letters that can be reported from a briefly flashed display is normally about four (12). Second, when observers have to detect a change in one of a varying number of objects form one display to the next (separated by a blank), accuracy data suggest that observers can hold about four items across displays (13-15, but see also 16).

Similar capacity estimates have been reached in typical attention tasks. For example, studies on attentional capture in which varying numbers of new objects appear abruptly in a visual search display indicate that up to four such abrupt onsets are prioritized (17). Similarly, up to four items may receive priority in visual search when pre-cued by place-holders (18, but see 19), and up to four objects may be successfully tracked in randomly moving dot arrays (20). Furthermore, a maximum of four distractors interferes with a central attention task (21). Finally, a classic finding is that displays consisting of one to approximately four items appear to be counted much more efficiently than displays of more than four (see 22, 23, for reviews), a functional distinction that has been supported by neuropsychological evidence (24).

On the basis of these and other findings, it has been proposed that the limitations in memory capacity in fact reflect the limitations in attention (11, 25). Interestingly, others have suggested that working memory capacity may really only be limited to one object at a time, instead of four (26). That is, multiple objects can be juggled by the memory system, but only one of these really receives the focus of processing. Interestingly, a similar one-object limitation has been suggested for the focus of attention (27, 28).

3.2. Shared control processes: Maintenance

A series of studies has suggested shared control mechanisms concerning the maintenance of information in visual working memory (see 29, for a review). The idea is that the retention of especially spatial visual information occurs through attention- or oculomotor-based rehearsal (30). For instance, a series of locations is being remembered by continuously or repeatedly attending to those locations. Earlier it was proposed that visuo-spatial information is maintained through programming (but not necessarily executing) a series of eye movements (31). In support of this idea, probes presented during the retention interval are better perceived, and result in stronger fMRI and ERP signals, when occurring at remembered locations as compared to irrelevant locations (32-34). Remembering a location also affects the oculomotor system, as eye movement trajectories curve away from the memorized location of an item in the same way as they do when the item is actually present (35). Moreover, spatial memory is impaired when observers are given a spatial attention or oculomotor task during the retention interval (and vice versa, spatial attention is impaired during an irrelevant spatial memory task), indicating that the visuo-spatial working memory – attention relationship is reciprocal (32, 36-38).

3.3. Shared control processes: Inhibition

An important function of working memory is to keep irrelevant information from interfering with behavior, through active inhibition (7, 39-43). Similar inhibitory processes have been proposed for attention (see 44, for a collection). The empirical link between the two has recently been made by Lavie and colleagues (45, 46). They found increased distractor interference in a visual search task, under conditions of high memory load. Apparently, the additional memory task drains cognitive control mechanisms necessary to suppress visual interference. Furthermore, it appears not so much the severity of the memory load (i.e. the number of items to be remembered) that causes increased interference, but the fact that the observer needs to maintain and coordinate two task sets. This suggests that what is to be suppressed is defined within a specific task set, and that only one task set can be fully maintained at a time.

4. SHARED CONTENT

4.1. Biased competition

If attention and working memory represent one and the same cognitive function, they should not only share capacity and control mechanisms, but also the same content. Probably the most influential model to date in which the identity relationship between attention and working memory is made explicit is Desimone and Duncan's *biased competition model* (47). According to this model, which perceptual content is selected for further processing is directly determined by the contents of working memory. For example, in a visual search task, in which observers are asked to search for a target among a number of irrelevant objects, a perceptual representation of the target will be pre-activated in anticipation of its appearance – activity which reflects the content of working memory. When the actual target appears, the very same perceptual representation is called for, and the presence of the preliminary activity will automatically provide it with an advantage over the other objects in the display, resulting in its selection. In other words, working memory and attention operate on the same content.

Support for the biased competition model comes from monkey physiology data of Chelazzi and colleagues (48). Trained monkeys were first presented with a single object, which they were required to remember. The initial object disappeared and was followed, after a few seconds, by the presentation of a visual search display containing multiple objects, one of which would be the same as the remembered object. The monkey's task was to make an eye movement to the object matching the remembered object, and thus involved both working memory and visual attention components. Cells in the inferior temporal cortex were found to be specifically sensitive to the target object, as revealed through increases in activity in response to the actual presence of the target in the initial memory display as well as the final visual search display. Importantly, the very same cells also showed increased activity during the interval between the memory and the search display, even though the actual target stimulus was no longer present. Apparently, not only the same brain areas, but even the same cells are involved in both the selection and the maintenance of perceptual representations. From these data, Desimone and Duncan (47) concluded that "[v]isual search simply appears to be a variant of a working memory task, in which the distractors are distributed in space rather than in time." (p. 207). Chelazzi and colleagues have also found supporting behavioral evidence in humans (49). They asked participants to search for a particular target object (e.g. a lock) in a briefly presented display containing several other objects. They found that observers were more distracted when one of the non-target objects was related to the target (e.g. a key), as indicated by eye movements, RTs, and memory reports. In line with the biased competition model, the activation of object representations in working memory primes associated representations, which automatically makes them attract more attention.

4.2. Setting some constraints: Working memory versus attentional set

Few scientists will doubt that looking for something involves some form of memory – if only because forgetting what one was looking for can be so awkward in everyday life. Here, following many others, I will refer to the activity of looking for some property or object as the active deployment of an *attentional set* for that property or object. The memory component of the attentional set involves maintaining some kind of description or template of what is to be selected. For example, when looking for your little red suede booklet in which you write down your spontaneous ideas, you may employ an attentional set for "red and small". However, the strong and therefore more interesting claim derived from the biased competition model is that a memory of something *is* an attentional set for that same thing. In other words, visually remembering your little red booklet automatically implies looking for your booklet. Of course, the alternative hypothesis is then that remembering something and looking for something are really two different activities. Specifically, an attentional set for an object – even though it requires working memory – may involve more than merely remembering or visualizing that object.

A strong claim needs a strong test. If we want to claim that working memory and attentional set are one and the same, then the optimal test is one in which the content of working memory and the attentional set are allowed to differ. If they then still interact, we have a case for unity. For example, while you are looking for the car keys, you remember to enter an idea in your red booklet. If we then find that you are distracted by that red stapler, then this provides strong evidence for working memory and attention sharing the same representations. In other words, to be able to reject the hypothesis that attentional set and working memory deserve to be different psychological constructs, one needs to at least give them the chance to try and behave as different constructs. Studies like the ones by Chelazzi and colleagues (as reviewed above) do not fulfill this requirement. In these studies, participants (monkey or human) were required to remember an object, and then look for the very same object in the subsequent display. It is then not surprising that working memory and attention interact. As we already know from studies on contingent attentional capture, the probability of selection of an item depends to a large extent on its similarity to the observer's attentional set (50, 51). Thus, the perceptual activation of objects in monkey IT cortex (48), or the attentional capture by semantically related objects in humans (49) may not reflect the contents of working memory per se, but the additional operations required for the maintenance of an active attentional set for those objects. As will be reviewed next, it has proven quite difficult to tear these possibilities apart.

4.3. Imagery

If one regards *imaging* as a form of visual working memory use, then content-specific interactions between memory and attention can be traced back to Farah's studies on imagery (52). Farah instructed participants to imagine either a T or an H, after which she faintly presented one of these letters in a two-alternative forced choice detection task. The imagined letter was not predictive of the presented letter, so in principle there was no reason for participants to also create an attentional set for the imagined letter. Nevertheless, the presented letters were better detected when they matched the mental image, a result that implies a common representational structure between perception and imagery. In a follow-up study (53), participants saw a grid of empty squares, and imagined the presence of either a T or an H on this grid by "mentally filling in" the corresponding squares. After they had formed the mental picture, the participants were required to detect a probe dot presented in one of the grid's squares. A greater bias (but not greater sensitivity) was found towards detecting probe dots for the area "occupied" by the imaged letter. Farah interpreted this bias as an attentional readiness to perceive the imagined letter.

Farah's findings resonate with more recent studies in which observers were explicitly provided with the memory content rather than being asked to imagine it themselves. In one study (54), participants were presented with a specific face to remember, after which the task changed to detecting a probe dot. The dot could appear on a background picture of the same face or on a picture of a different face, presented to either side of fixation. Response times (RTs) were faster when the dot appeared on the memory-matching face, suggesting that working memory affected visual selection – even though the memory content was irrelevant to the task. A similar manipulation was used to test a group of parietal patients demonstrating visual extinction of contra-lesional stimuli (55). It was found that the extinction was reduced when the contra-lesional stimulus matched an earlier presented stimulus that had to be remembered. No such improvements were found when the initial stimulus only needed to be viewed or identified.

One potential problem with these manipulations is that although nominally, the memorized or imagined items are irrelevant to the visual task, in practice, observers may perceive this differently, as there is still a 50% likelihood of a match between the memory item and the visual target. For example, observers may have deliberately chosen to attend more to an object when instructed to imagine or remember that same object, because they thought it might help them refresh their memory. Alternatively, biases towards the memory-matching item may occur on the basis of implicit learning due to incidental streaks of trials on which the visual target was repeatedly identical or coupled to this item (56). In any case, in these tasks there was nothing much to lose by deliberately attending to the remembered item.

A stronger test for automatic, memory-driven attention is therefore provided by studies in which the memory-matching item is *never* the target, and thus, when attended, is actually detrimental to the task. Such a test was first provided by Pashler and Shiu (57). They asked participants to form and remember a mental image of an object, and then to concentrate on the main task of extracting a target digit from a rapid sequence of distractor pictures, one of which was of the imagined object. Consistent with memory-driven attentional capture, the matching distractor picture resulted in reduced detection of a subsequently presented target digit. However, this study also fails to provide unequivocal evidence for a role of visual working memory in inducing this capture. The capture may have been caused by perceptual priming, rather than by memory, as the brief activation of an image in itself may be sufficient to induce prioritization of a matching object (58). Indeed, Pashler and Shiu found interference of the imagined object even when observers were instructed to discard rather than to remember the initial image.

4.4. Memory-driven attentional capture in visual search

Recently, Olivers and colleagues employed a method that circumvents most of the problems outlined above (59). Figure 2 shows the main procedure, which consisted of two tasks. Observers were asked to remember a particular color (red, green, blue or yellow). At the end of the trial, their memory was tested by asking them to choose the original color from a set of three alternatives. There were two versions of the memory task. In what was assumed to be the "more verbal" version, the memory test consisted of easily distinguishable alternatives for which verbal labels are readily available, for example red, green,

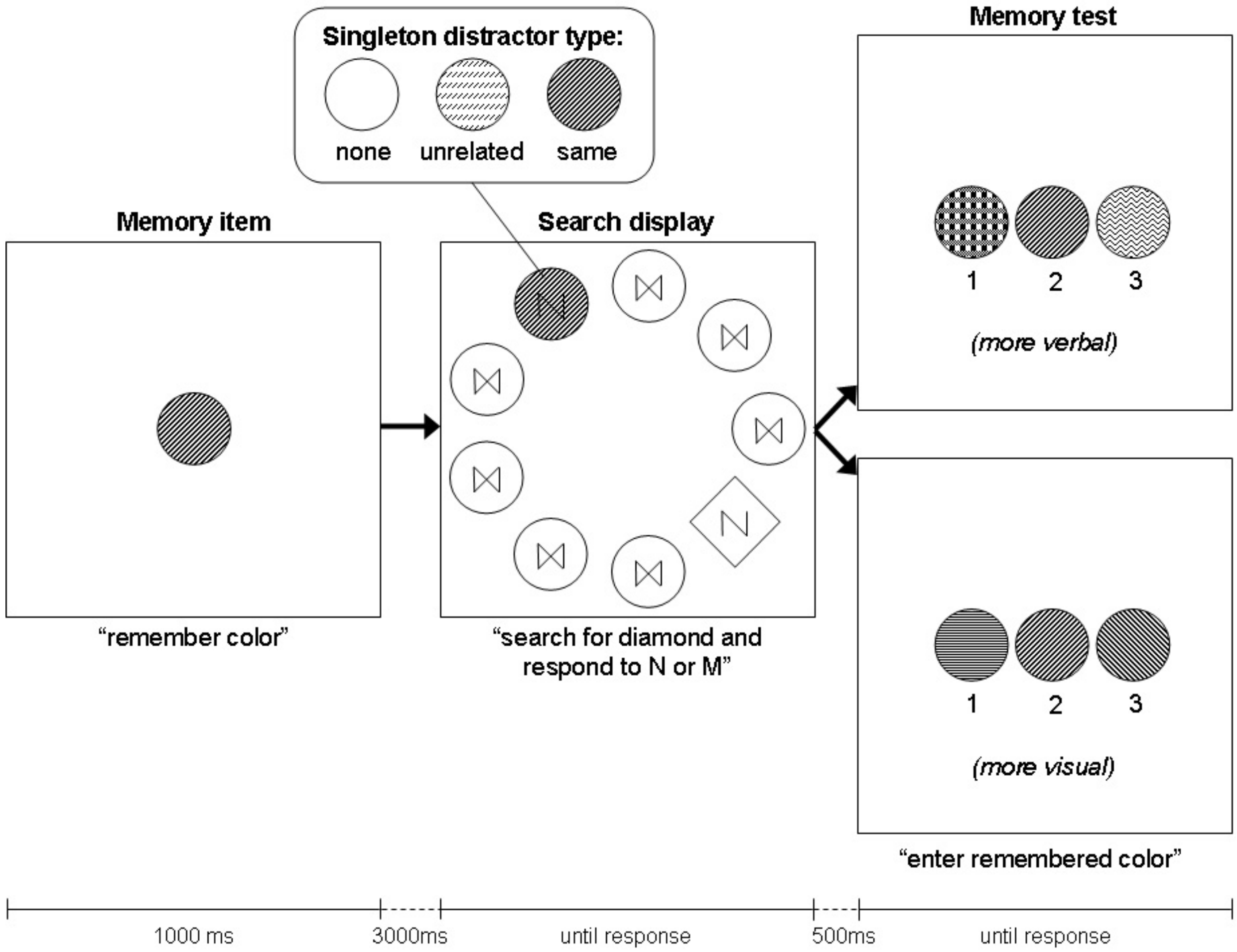

Figure 2. Experimental procedure used by Olivers and colleagues (59). Observers were required to remember a color. They then performed a search for a diamond shape and responded to the N or M inside (here N). At the end of the trial, observers chose the color they remembered from three alternatives. These alternatives could be distinctive, canonical colors (more verbal condition), or they could be subtle shades of the same color (more visual condition). Reproduced with permission from ref. 59 (American Psychological Association).

and blue. In this task it is sufficient to store the verbal label without having to put much effort in trying to create a visual memory of the exact shade of red. In contrast, in the "more visual" version, the to-be-remembered color had to be distinguished from highly similar colors from the same category. For example, a particular shade of red had to be distinguished from other shades of red. It was assumed that observers would use their visual working memory – probably not exclusively so, but more so in this condition than in the more verbal condition.

Then, a few seconds after the to-be-memorized item had disappeared, the task changed to a visual search task. The target was always a grey diamond among grey disk-shaped distractors. Participants responded to the identity of the letter presented inside the diamond. On many trials, however, one of the distractors carried a unique color. Previous studies have shown that such salient distractors capture attention, as indicated by elevated RTs relative to conditions in which no such distractor is present (60, 61). Figure 3 shows the main results. The important finding here was that the interference was stronger for distractors that matched the content of memory than for unrelated color distractors. The other important finding was that this was only the case for the "more visual" memory condition. In the "more verbal" condition there was no effect of the relationship between the visual distractor and the contents of memory. Note that participants had no reason to attend to the distractor: It only interfered with the goal of responding to the gray diamond. Thus, these results are consistent with the idea that visual working memory and attentional set are at least partly the same in terms of content.

Before we can draw this conclusion, however, we need to carefully consider some alternatives. First, was there really no reason for participants to attend to the distractor? Might they perhaps use it to refresh their memory? To control for this possibility, subsequent experiments used similar, but never exactly the same colors

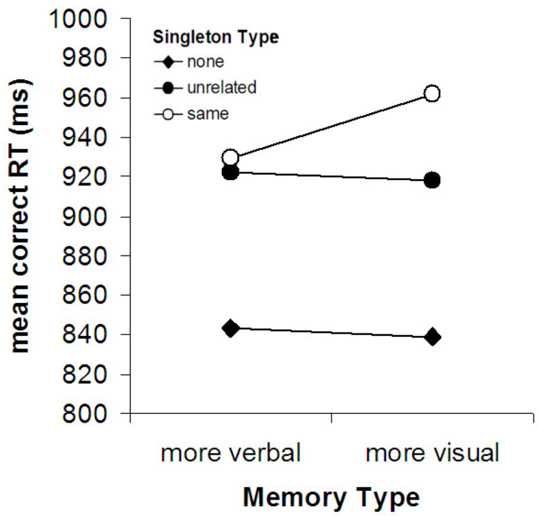

Figure 3. Results of Experiment 2 of Olivers and colleagues (59). Visual search RTs are shown for displays in which no singleton distractor was present, a singleton distractor was present but unrelated to the memory content, or a singleton distractor was present that matched the color of the memorized item. Increased interference was found for the latter, but only in the more visual memory condition. Reproduced with permission from ref. 59 (American Psychological Association).

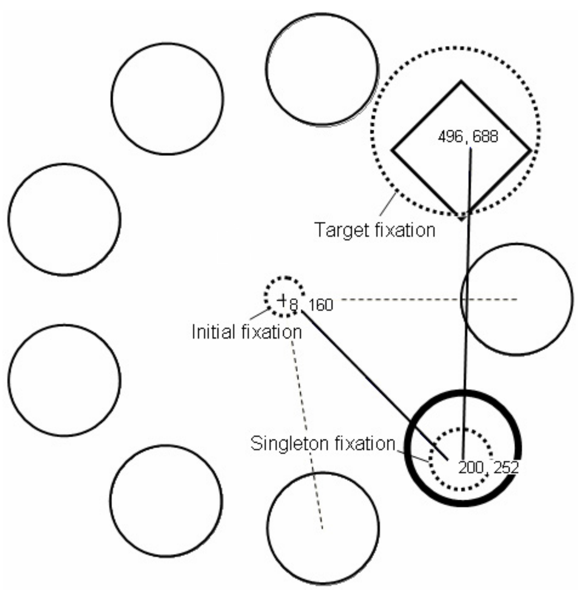

Figure 4. Example eye movement pattern from Olivers and colleagues (59). The diamond was the target, the bold disk represents the uniquely colored distractor (which on this trial was related to the memory content). The dashed lines represent the area within which an eye movement was regarded as captured by the distractor. The dashed circles and solid lines represent fixations and eye movements respectively, with larger circles representing longer fixation durations. The pair of numbers corresponds to the start time (relative to the start of the trial) and duration of the fixation. Reproduced with permission from ref. 59 (American Psychological Association).

for the memory item and the colored distractor (participants were informed about this). Attending to the distractor would therefore only make the memory task more difficult. The results remained the same: The similar distractors interfered more with search than distractors that were unrelated to the memory content.

Second, might the stronger attentional capture be explained through implicit priming by the preceding presentation of the memory item, rather than through explicit working memory storage of the same item? The answer is no, since priming should then have been the same in the more verbal memory condition in which exactly the same memory item was presented. Furthermore, in a follow-up experiment, participants initially studied two colors. Only afterwards they were told that they should remember only one of the two and forget about the other. Implicit priming effects should be the same for the two colors, yet only the relevant color led to increased distractor effects. These results demonstrate that it is the active keeping in mind of a feature or object that biases attention in this task, not some implicit memory trace.

A third possibility is that it is not so much the *maintenance* of an item which interacts with attention, but the *encoding*. When participants are presented with the initial to-be-memorized item, it is most likely that they pay attention to that item in order to encode it into memory. Perhaps then, when the visual search display appears, participants are still encoding the first display, and attention simply follows the matching item (which is now a distractor). Indeed, in studies in which the time between the memory item and the search display was very short (62, 63), this may well have been the case. The Olivers *et al.* study (59), however, deliberately used breaks of several seconds between the memory task and the visual search task. By any realistic information processing account, memory encoding should be over by then.

Finally, there is the possibility that the contents of working memory did not affect selective attention itself, but processing stages after selection. For example, the capture of attention by memory-matching and non-matching distractors may initially be equally strong, but it may be more difficult to disengage attention from items that match the memory item. Although this still suggests a strong link between working memory and attention, it is not the same as stating that to maintain something in working memory is identical to maintaining an attentional set. To investigate these potential scenarios, an eye movement study was conducted, of which an example trial is shown in Figure 4. The idea was that if the memory-matching distractor captures attention more often than non-matching distractor, then more eye movements will be made towards it. If the memory-matching distractor is only more difficult to reject, then we should see an effect on the length of time the eyes linger on the item, not on how often they go there. The results supported the first prediction: The eyes went to the matching distractor on 63% of the trials, to the non-matching distractor on 48%. Once captured, however, the eyes remained on the distractor for about 150 ms in both conditions. In other words, the memory content affected the selection of the distractor, not its rejection.

5. WORKING MEMORY AND ATTENTION: A CASE FOR A DIVORCE?

5.1. Separate capacities?

The evidence reviewed so far suggests that visual working memory and attention might best be treated as one and the same. However, there is now also considerable evidence that, despite some functional overlap, we are dealing with two different mechanisms. For example, one study assessed visual search performance when observers had to simultaneously remember a set of up to four objects (64). The idea was that if visual working memory is filled to the brim, there is no capacity for the search target, and visual search should become less efficient (e.g. because time-consuming memory swapping needs to take place). This is not what happened: Although overall search RTs increased with higher memory load, search efficiency (as expressed by the slopes of the RT x set size functions) remained the same. Thus, the memory load caused some additional overhead costs, but did not interfere with attention per se, suggesting that the contents of working memory and attentional set could be kept separate.

An important question here is whether it is always working memory that is involved in maintaining an attentional set for the target. In many a search task, observers are searching for the same object or set of objects for hundreds to thousands of trials. Search may to a large extent become automatic without the need to actively preserve or refresh an attentional set on every trial (65). Rather than involving explicit working memory, such automaticity may be based on implicit memory traces of the target, resulting in priming from one trial to the next, without much conscious control (66). This way, loading working memory would be expected to have little effect on search.

5.2. Separate content?

Other evidence for separate functionality comes from a neuropsychological study on patients with damage to the inferior frontal cortex (67). Just as for normal observers (62, 63), search times were modulated by the match between objects in the search display and the to-be-remembered object. However, the important finding here was that in the frontal patient group, search was much more affected by the memory content than in the age-matched control group, suggesting the patients had more trouble keeping working memory and attentional content separate. Conversely then, this implies that under normal functioning, working memory and attentional representations can be kept relatively shielded from each other.

The same conclusion can be reached on the basis of a number of visual search studies (68-70). Observers were asked to remember one object, and then search for another object. The memory object could then return as a distractor in the visual search task. However, unlike the earlier discussed studies of memory-based interference in visual search (59, 62), neither of these studies provided evidence for increased interference for matching distractors – whether measured through RTs, errors, or eye movements. These failures to find an interaction have led to the conclusion that visual working memory is fractionated, allowing for multiple representations to co-exist without affecting each other. Alternatively, the search template may have a special status within working memory that allows it to guide attention, whereas items that are not currently relevant are represented in a weaker form – just sufficiently active to be retrieved for later use, but not active enough to guide current behavior. Interestingly, one of these studies found search to be even *faster* when distractors matched the memory item, leading to the conclusion that the contents of working memory can be flexibly and strategically used to inhibit irrelevant information in the attention task (70).

How can the discrepancies between studies that found increased interference from memorized items on visual search (59, 62, 63, 67) and studies that did not (68-70, see also 71) be explained? There are some differences in procedures that may allow for such discrepancies. For example, studies that failed to find an interaction not only varied the "irrelevant" working memory item from trial to trial, but also the search target (68, 69). The additional working memory capacity required for this may have been at the expense of the irrelevant item, resulting in a weak or shielded representation (72). In another case (70), the search target and to-be memorized item were always highly similar (both boxes with a gap in one of the sides), which may have required the active suppression of one of the two to prevent interference within working memory itself. This suppression may then have carried over to the search display. Moreover, the studies that failed to find memory-driven interference often used articulatory suppression tasks to force the use of visual working memory. Perhaps the additional task of having to suppress verbal coding led to a further weakening or deprioritizing of memory representations. In addition, in these studies, search itself was usually slow and serial, possibly further draining the system. A final difference was that the visual search displays in these studies were heterogeneous, making it difficult for the distractor to stand out.

In contrast, in the studies of Olivers and Soto and their colleagues (59, 62), the search target was always the same, and bore hardly any similarity to the to-be-memorized item. Moreover, search itself was overall easier and more efficient, with displays in which objects were generally highly discriminable, or even uniquely salient. Together, this may have allowed for more automatic search processes, while full working memory capacity could be dedicated to the to-be-memorized item, with stronger memory effects on visual attention as a consequence. We are currently exploring these differences in a number of experiments. The preliminary results suggest that the exact procedure for invoking visual working memory (whether through articulatory suppression or otherwise) made little difference. Nor did the heterogeneity or overall difficulty of the visual search displays. What did appear to matter was whether observers were required to remember both the search target and the memory item on each trial. Consistent with earlier proposals (72), when observers were presented with a new, to-be-remembered target on each trial (varied mapping), the other memory item (irrelevant to the search task) lost its effect on search. Apparently, only one item within memory really receives the focus of activity, at the expense of other, to-be-remembered items.

6. CONCLUSIONS

It is evident that more research is required to be able to answer the question whether or not the traditionally separate constructs of visual working memory and visual attention are better merged. We have seen evidence that visual working memory and attention share the same capacity, share the same control processes, and finally, share the same content. It appears then that we can speak of a collection of attentional mechanisms that enhance and maintain relevant information, while inhibiting irrelevant information. When these same mechanisms are operational in the absence of the actual stimulus, we speak of working memory.

However, demonstrating the unison of perceptual and mnemonic representations has met with some obstinate methodological problems, involving alternative hypotheses on priming and mnemonic strategies. In fact, it will be difficult to demonstrate or prove false the unity between two concepts, when there is no agreed upon unity *within* those concepts in the first place. For example, does actively suppressing items require an attentional set? Are non-suppressed, but slumbering items under attentional control? Are such items selected, are they candidates for selection, or are they more than any other item excluded from selection? Note how we could easily exchange this attentional terminology for working memory related terms without bringing us any closer to an answer to these questions (e.g. are suppressed items maintained inside or outside working memory?).

Moreover, memory-based interference effects have generally been weak, often absent, and sometimes even turned into benefits. Taken together, this has led some researchers to conclude that thinking of something really differs from looking for something. This is probably too rigorous a stance. Although the honeymoon may have ended, the marriage between visual working memory and attention has not yet. Working memory and attention appear to share many things, except perhaps their priorities. Following Oberauer's idea (26), perhaps the most elegant model is the one that assumes that multiple representations can be kept somewhat active, but only one of these is in the current focus of attention. While this one representation has perceptual priority (and we call it attention), the others are kept in a slumbering or suppressed mnemonic state (and we call it working memory). Our ultimate goal is to unravel the mechanisms on how the cognitive system can so flexibly juggle these multiple representations. Whether we call such mechanisms attention or working memory, is, as Houtkamp and Roelfsema (69) rightly pointed out, merely a question of semantics.

7. ACKNOWLEDGEMENT

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8. REFERENCES

1. Logie, R. H.: Visuo-spatial working memory. Lawrence Erlbaum, Hove, UK (1995)
2. Treisman, A. & G. Gelade: A feature-integration theory of attention. Cognitive Psychology, 12, 97-136 (1980)
3. Cabeza, R. & L. Nyberg: Imaging cognition: an empirical review of PET studies with normal subjects. *J. Cog. Neurosci*, 9, 1-26 (1997)
4. Cabeza, R. & L. Nyberg: Imaging cognition II: An empirical review of 275 PET and fMRI studies. *J. Cog. Neurosci*, 12, 1-47 (2000)
5. Corbetta, M. & G. L. Shulman: Imaging expectations and attentional modulations in the human brain. In: Visual attention and cortical circuits. Eds: J. Braun, C. Koch&e. al., (2001)
6. D'Esposito, M.: Functional neuroimaging of working memory. In: Handbook of Functional Neuroimaging of Cognition. Eds: R. Cabeza&A. Kingstone. MIT Press, Cambridge, MA (2001)
7. Fuster, J. M.: The prefrontal cortex: Anatomy, physiology, and neuropsychology of the frontal lobe. Lippincott Williams & Wilkins, New York (1997)
8. Handy, T. C., J. B. Hopfinger & G. R. Mangun: Functional neuroimaging of attention. In: Handbook of Functional Neuroimgaing of Cognition. Eds: R. Cabeza&A. Kingstone. MIT Press, Cambridge, MA (2001)
9. Kanwisher, N. & E. Wojciulik: Visual attention: Insights from brain imaging. *Nature Reviews: Neuroscience*, 1, 91-100 (2000)
10. Kastner, S. & L. G. Ungerleider: Mechanisms of visual attention in the human cortex. *Annu. Rev. of Neurosci*., 23, 315-341 (2000)
11. Cowan, N.: The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behav. Brain Sci*., 24, 87-185 (2000)
12. Sperling, G.: The information available in brief visual presentations. *Psychological Monographs*, 74, whole issue (1960)
13. Phillips, W. A.: On the distinction between sensory storage and short-term visual memory. *Perception & Psychophysics*, 16, 283-290 (1974)
14. Pashler, H.: Familiarity and visual change detection. *Perception & Psychophysics*, 44, 369-378 (1988)
15. Luck, S. J. & E. K. Vogel: The capacity of visual working memory for features and conjunctions. *Nature*, 390, 279-281 (1997)
16. Alvarez, G. A. & P. Cavanagh: The capacity of visual short-term memory is set both by visual information load and by number of objects. *Psychological Science*, 15, 106-111 (2004)
17. Yantis, S. & D. N. Johnson: Mechanisms of attentional priority. 16, 812-825 (1990)
18. Burkell, J. A. & Z. W. Pylyshyn: Searching through subsets: A test of the Visual Indexing Hypothesis. *Spatial Vision*, 11, 225-258 (1997)

19. Franconeri, S. L., G. A. Alvarez & J. T. Enns: How many locations can you select? *J. Exp. Psychol.: Hum. Perc. Perf.* (in press)
20. Pylyshyn, Z. & R. W. Storm: Tracking Multiple Independent Targets: Evidence for a Parallel Tracking Mechanism. *Spatial Vision*, 3, 179-197 (1988)
21. Lavie, N. & S. Cox: On the Efficiency of Visual Selective Attention: Efficient Visual Search Leads to Inefficient Distractor Rejection. *Psychological Science*, 8, 395-398 (1997)
22. Mandler, G. & B. J. Shebo: Subitizing: An analysis of its component processes. *J. Exp.Psychol.: Gen.*, 111, 1-22 (1982)
23. Trick, L. M. & Z. W. Pylyshyn: Why are small and large numbers enumerated differently? A limited-capacity preattentive stage in vision. *Psychological Revie*w, 101, 80-102 (1994)
24. Dehaene, S. & L. Cohen: Dissociable mechanisms of subitizing and counting: Neuropsychological evidence from simultanagnosic patients. ? *J. Exp. Psychol.: Hum. Perc. Perf.*, 20, 958-975 (1994)
25. Klahr, D.: Quantification processes. In: Visual information processing. Ed: W. G. Chase. Academic, Oxford, England (1973)
26. Oberauer, K.: Access to information in working memory: Exploring the focus of attention. *J. Exp. Psychol.: Learn. Mem. and Cogn.*, 28, 411-421 (2002)
27. Duncan, J.: The Demonstration of Capacity Limitation. *Cogn. Psychol*., 12, 75-96 (1980)
28. Broadbent, D. E. & M. H. P. Broadbent: From detection to identification: Response to multiple targets in rapid serial visual presentation. *Perception & Psychophysics*, 42, 105-113 (1987)
29. Awh, E. & J. Jonides: Overlapping mechanisms of attention and spatial working memory. *Trends Cogn. Sci.*, 5, 119-126 (2001)
30. Smyth, M. M. & K. A. Scholey: Interference in immediate spatial memory. *Memory and Cognition*, 22, 1-13 (1994)
31. Baddeley, A.: Working Memory. Oxford University Press, New York (1986)
32. Awh, E., J. Jonides & P. A. Reuter-Lorenz: Rehearsal in spatial working memory. *J. Exp. Psychol.: Hum. Perc. Perf.,* 24, 780-790 (1998)
33. Awh, E., J. Jonides, E. E. Smith, R. B. Buxton, L. R. Frank, T. Love, E. C. Wong & L. Gmeindl: Rehearsal in spatial working memory: Evidence from neuroimaging. *Psychological Science*, 10, 433-437 (1999)
34. Awh, E. & J. Jonides: The role of spatial selective attention in working memory for locations: Evidence from event-related potentials. *J. Cog. Neurosci*, 12, 840-847 (2000)
35. Theeuwes, J., C. N. L. Olivers & C. L. Chiszk: Remembering a location makes the eyes curve away. *Psychological Science*, 16, 196-199 (2005)
36. Baddeley, A. & K. Lieberman: Spatial working memory. In: Attention and Performance VIII. Ed: R. S. Nickerson. Lawrence Erlbaum, (1980)
37. Schmidt, B. K., E. K. Vogel, G. F. Woodman & S. J. Luck: Voluntary and automatic attentional control of visual working memory. *Perception & Psychophysics*, 64, 754-763 (2002)
38. Woodman, G. F. & S. J. Luck: Visual search is slowed when visuospatial working memory is occupied. *Psychonomic Bull. Rev.*, 11, 269-274 (2004)
39. Engle, R. W., A. R. A. Conway, S. W. Tuholski & R. J. Schisler: A resource account of inhibition. *Psychological Science*, 6, 122-125 (1995)
40. Hasher, L. & R. T. Zacks: Working memory, comprehension, and aging. In: The psychology of learning and motivation: Advances in research and theory. Ed: G. H. Bower. Academic Press, San Diego, CA (1988)
41. Jonides, J., E. E. Smith, C. Marshuetz, R. A. Koeppe & P. A. Reuter-Lorenz: Inhibition in verbal working memory revealed by brain activation. *Proc. Natl. Acad. Sci. USA*, 95, 8410-8413 (1998)
42. Lavie, N.: Selective attention and cognitive control: Dissociating attentional functions through different types of load. In: Control of Cognitive Processes: Attention and Performance XVIII. Eds: S. Monsell&J. Driver. Bradford, MIT Press, Cambridge, MA (2000)
43. Miller, E. K. & J. D. Cohen: An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, 24, 167-202 (2001)
44. Dagenbach, D. & T. H. Carr: Inhibitory processes in attention, memory, and language. Academic Press, (1994)
45. Lavie, N., A. Hirst, J. W. d. Fockert & E. Viding: Load theory of selective attention and cognitive control. *J. Exp. Psychol.: Gen.*, 133, 339-354 (2004)
46. Lavie, N. & J. W. De Fockert: The role of working memory in attentional capture. *Psychonomic Bull. & Rev.*, 12, 669-674 (2005)
47. Desimone, R. & J. Duncan: Neural Mechanisms of Selective Visual Attention. *Annual Review of Neurosci*ence, 18, 193-222 (1995)
48. Chelazzi, L., E. K. Miller, J. Duncan & R. Desimone: A neural basis for visual search in inferior temporal cortex. *Nature*, 363, 345-347 (1993)
49. Moores, E., L. Laiti & L. Chelazzi: Associative knowledge controls deployment of visual selective attention. *Nature Neuroscience*, 6, 182-189 (2003)
50. Folk, C., R. W. Remington & J. C. Johnston: Involuntary covert orienting is contingent on attentional control settings. *J. Exp. Psychol.: Hum. Perc. Perf.*, 18, 1030-1044 (1992)
51. Folk, C. L., A. B. Leber & H. E. Egeth: Made you blink! Contingent attentional capture produces a spatial blink. *Perception & Psychophysics*, 64, 741-753 (2002)
52. Farah, M. J.: Psychophysical evidence for shared representational medium for mental images and percepts. *J. Exp. Psych.: Gen.*, 114, 91-103 (1985)
53. Farah, M. J.: Mechanisms of imagery-perception interaction. *J. Exp. Psychol.: Hum. Perc. Perf.* , 15, 203-211 (1989)
54. Downing, P. E.: Interactions between visual working memory and selective attention. Psychological Science, 11, 467-473 (2000)
55. Soto, D. & G. W. Humphreys: Seeing the content of the mind: Enhanced awareness through working memory in patients with visual extinction. *Proc. Natl. Acad. Sci. USA*, 103, 4789-4792 (2006)
56. Kristjánsson, Á. & K. Nakayama: A primitive memory system for the deployment of transient attention. *Perception & Psychophysics*, 65, 711-724 (2003)

57. Pashler, H. & L. P. Shiu: Do images involuntarily trigger search? A test of Pillsbury's hypothesis. *Psychonomic Bull. & Rev.*, 6, 445-448 (1999)
58. Theeuwes, J., B. Reimann & K. Mortier: Visual search for featural singletons: no top-down modulation, only bottom-up priming. *Visual Cognition*, 14, 466-489 (2006)
59. Olivers, C. N. L., F. Meijer & J. Theeuwes: Feature-based memory-driven attentional capture: Visual working memory content affects visual attention. *J. Exp. Psychol.: Hum. Perc. Perf.*, 32, 1243-1265 (2006)
60. Theeuwes, J.: Cross-dimensional perceptual selectivity. *Perception & Psychophysics*, 50, 184-193 (1991)
61. Theeuwes, J.: Perceptual selectivity for color and form. *Perception & Psychophysics*, 51, 599-606 (1992)
62. Soto, D., D. Heinke, G. W. Humphreys & M. J. Blanco: Early, involuntary top-down guidance of attention from working memory. *J. Exp. Psychol.: Hum. Perc. Perf.*, 31, 248-261 (2005)
63. Soto, D., G. W. Humphreys & D. Heinke: Working memory can guide pop-out search. *Vision Res.*, 46, 1010-1018 (2006)
64. Woodman, G. F., E. K. Vogel & S. J. Luck: Visual search remains efficient when visual working memory is full. *Psychological Science*, 12, 219-224 (2001)
65. Schneider, W. & R. M. Shiffrin: Controlled and Automatic Human Information Processing: I. Detection, Search, and Attention. *Psychological Review*, 84, 1-66 (1977)
66. Maljkovic, V. & K. Nakayama: Priming of pop-out: I. Role of features. *Memory and Cognition*, 22, 657-672 (1994)
67. Soto, D., G. W. Humphreys & D. Heinke: Dividing the mind: The necessary role of the frontal lobes in separating memory from search. *Neuropsychologia*., 44, 1282-1289 (2006)
68. Downing, P. E. & C. M. Dodds: Competition in visual working memory for control of search. *Visual Cognition*, 11, 689-703 (2004)
69. Houtkamp, R. & P. R. Roelfsema: The effect of items in working memory on the deployment of attention and the eyes during visual search. *J. Exp. Psychol.: Hum. Perc. Perf.*, 32, 426-442 (2006)
70. Woodman, G. F. & S. J. Luck: Do the contents of visual working memory automatically influence attentional selection during visual search? *J. Exp. Psychol.: Hum. Perc. Perf.* (in press)
71. Varakin, D. A. & D. T. Levin: Visual working memory matches do not always attract attention [Abstract]. *Journal of Vision*, 6, 134a (2006)
72. Oh, S.-H. & M.-S. Kim: The guidance effect of working memory load on visual search. (Abstract). *Journal of Vision*, 3, 629a (2003)

Abbreviations: ERP: event-related potentials; fMRI: functional magnetic resonance imaging; PET: positron emission tomography; RT: reaction time

Key Words: Working Memory, Attention, Visual Search, Attentional Capture, Attentional Capacity, Inhibition, Maintenance, Imagery, Review

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