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Conscious Visual Memory With Minimal Attention

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Is conscious visual perception limited to the locations that a person attends? The remarkable phenomenon of change blindness, which shows that people miss nearly all unattended changes in a visual scene, suggests the answer is yes. However, change blindness is found *after* visual interference (a mask or a new scene), so that subjects have to rely on working memory (WM), which has limited capacity, to detect the change. Before such interference, however, a much larger capacity store, called fragile memory (FM), which is easily overwritten by newly presented visual information, is present. Whether these different stores depend equally on spatial attention is central to the debate on the role of attention in conscious vision. In 2 experiments, we found that minimizing spatial attention almost entirely erases visual WM, as expected. Critically, FM remains largely intact. Moreover, minimally attended FM responses yield accurate metacognition, suggesting that conscious memory persists with limited spatial attention. Together, our findings help resolve the fundamental issue of how attention affects perception: Both visual consciousness and memory can be supported by only minimal attention.

Keywords: attention, perception, memory, consciousness

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Consciousness is one of the more elusive mysteries of science. How do the mechanistic interactions of trillions of unconscious particles lead to a rich inner life and vivid perceptual experiences? The global workspace theory (Baars, 1988, 2005; Dehaene & Naccache, 2001) is arguably the most prominent explanation of consciousness. According to this hypothesis, a limited subset of all the neurally processed information is selected for the "global workspace." Only this information is broadcasted to many parts of the brain and reaches consciousness in the process. Thus, the global workspace theory envisions a tight connection between selective mechanisms that highlight a limited subset of information (i.e., attention) and consciousness (Baars, 2002; Dehaene & Naccache, 2001).

The phenomenon of *change blindness* supports the view that attention is crucial for conscious perception. (Noë & O'Regan, 2000; Rensink, 2000). Change blindness occurs when subjects are shown two images in succession, separated by a brief blank, and they have to indicate whether a change has occurred. In contrast with most people's intuitions (Levin, Momen, Drivdahl, & Simons, 2000), subjects perform poorly in this task. Generally,

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subjects can detect changes only at locations that they attended to in both images (Rensink, 2002; Rensink, O'Regan, & Clark, 1997; Simons & Levin, 1997; Simons & Rensink, 2005), suggesting that their initial conscious perception was limited to these attended locations.

Strictly speaking, change blindness does not tap directly into visual perception but into visual short-term memory (VSTM), because for successful change detection, information about a previously viewed scene has to be recalled. It seems reasonable to take VSTM as a proxy measure of conscious perception. If one has consciously perceived a stimulus, one can probably recall it just moments later and vice versa; if one has not consciously perceived a stimulus, it seems unlikely that one can consciously recall it. Indeed, the same type of reasoning is often employed in masking experiments. In those experiments, a stimulus is shown briefly, followed by a mask. If subjects can consciously recall anything about the stimulus, it is concluded that the stimulus was consciously perceived, yet if they fail to recall any information, the stimulus is deemed to have been processed unconsciously (Dehaene, 2011; Hannula, Simons, & Cohen, 2005).

However, it appears that the claims of global workspace and the change blindness results are contradicted by everyday visual experiences. Introspectively, visual experiences seem rich and detailed, not limited and dependent on selective attention (Block, 2011; Lamme, 2003; Lamme & Roelfsema, 2000). How can this be reconciled with the change blindness results? It should be noted that VSTM seems to consist of three different storages: iconic memory (IM; Sperling, 1960), fragile memory (FM; Landman, Spekreijse, & Lamme, 2003; Pinto, Sligte, Shapiro, & Lamme, 2013; Sligte, Scholte, & Lamme, 2008), and working memory (WM; Sligte et al., 2008). IM exists approximately from disappearance of the memory display until 250 ms after offset. FM exists from 250 ms to 3 s after offset. Crucially, both IM and FM can be completely erased by masks and other interfering visual stimuli (Pinto et al., 2013; Sligte et al., 2008). WM exists from offset of the memory display until 3–5 s after offset. Yet, unlike IM and FM, WM is still available after visual interference (Pinto et al., 2013; Sligte et al., 2008). The problem is that in the studies documenting the change blindness phenomenon, VSTM is assessed *after* new, and possibly interfering, information has been presented. Subject have to compare the currently visible scene to the previous scene, so they have to recall information *after* new visual information has been perceived. Therefore, change blindness proves only that WM is poor and dependent on attention. Consequently, the crucial question, and the question of our current research, is whether all of VSTM, including IM and FM, is critically dependent on selective attention or whether only WM requires attention.

What is the most likely effect of withdrawal of (most) attention if VSTM is probed before and after visual interference, respectively? We argue that this depends on the relation between FM and WM (see Table 1 and Figure 1). Broadly speaking, there are two extreme possibilities. Either all stored items are doubly represented in both FM and WM (the one-component model) or information stored in FM is not stored in WM and vice versa (the two-component model). After visual interference, only WM is available, but before visual interference, both FM and WM are available. Thus, if FM and WM are separable components, capacity before visual interference is actually the sum of FM (or FM-*core,* as we call it) and WM. In that case, if withdrawing attention erases WM but leaves FM-core untouched, then both before and after visual interference, attentional diversion leads to the same capacity loss (here defined as the diminishing of capacity when attention is diverted, compared to when attention is distributed spontaneously). Conversely, if the one-component model is correct, and withdrawing attention erases only WM, then attentional diversion causes no capacity loss if VSTM is assessed before visual interference.

IM, FM, and WM can be gauged by using a change detection paradigm in combination with either a retrocue or a postcue (see Figure 2). Subjects compare a memory display with a successively presented test display (separated by a blank screen to prevent low-level motion cues). For instance, they indicate whether the orientations of the rectangles in a memory display and subsequent test display are identical. Furthermore, a cue highlights one location. Subjects are instructed that only the rectangle at the cued location may change its orientation from memory to test display. In 50% of cases there is a change, and in 50% there is no change. Crucially, the cue comes either during the blank between memory and test display, which is the retrocue condition, or together with the test display, which is the postcue condition. In the retrocue condition, the subject can recall the relevant information—that is, the orientation of the rectangle at the cued location in the memory display—before interfering information (the test display) has been presented. However, in the postcue condition, the relevant information can be recalled only after interfering visual information (the test display) has been presented. Thus, in the retrocue condition, IM or FM are assessed (depending on the time between appearance of the retrocue and the offset of the memory display), whereas in the postcue condition, WM is measured. Capacity is defined as the number of objects stored in memory and is derived from the accuracy and the number of items in the memory display (Cowan, 2001). Note that we refer to capacity as the number of distinct objects stored, because the displays consist of stimuli that are highly distinguishable (itemized oriented rectangles). However, this does not imply that slotlike behavior of VSTM always

Table 1
Overview of the Three Stages of VSTM, Including the Architecture of VSTM Before Visual Interference, According to the Two-Component Model

Stage	Item capacity	Existence	Before visual interference
IM	7–30	<.5 s before visual interference	$IM_{total} = IM_{core} + WM$
FM	6–16	.5–3 s before visual interference	$FM_{total} = FM_{core} + WM$
WM	2–5	0–3 s before and after visual interference	$WM = WM_{core}$

Note. VSTM = visual short-term memory; IM = iconic memory; FM = fragile memory; WM = working memory.

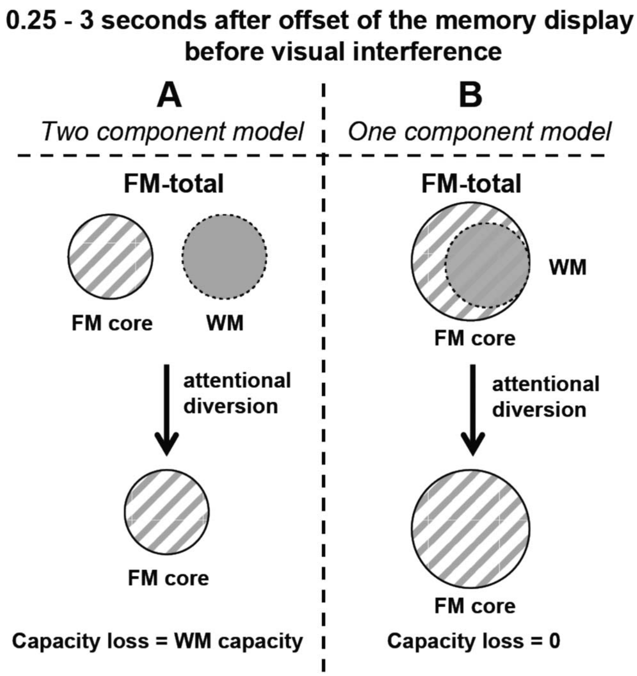

Figure 1. Two hypotheses on how attentional diversion impacts visual short-term memory (VSTM) before visual interference. VSTM consists of iconic memory (IM), fragile memory (FM, or FM-core), and working memory (WM). From 250 ms to 3,000 ms after offset, but before visual interference, both FM-core and WM are available. If FM-core and WM are two separable components (see Panel A) and withdrawal of attention erases only WM, then attentional diversion will cause a capacity loss equal to the capacity of WM (thus, capacity loss when VSTM is probed before and after visual interference is the same). However, if FM-core and WM are part of the same component (see Panel B) and attentional diversion erases only WM, then capacity loss will be zero if VSTM is assessed before visual interference. Alternatively, partially coinciding components is also a possibility. Last, only if FM-core is also diminished by attentional withdrawal can capacity loss caused by attentional diversion be larger when VSTM is probed before visual interference than when VSTM is probed after visual interference.

emerges or that VSTM is ultimately slot-based or resource-based (Bays, Catalao, & Husain, 2009; Franconeri, Alvarez, & Cavanagh, 2013; Luck & Vogel, 1997; Luck & Vogel, 2013).

Previous research has found that performance in the retrocue condition is much more accurate than in the postcue condition (Pinto et al., 2013; Sligte, Scholte, & Lamme, 2008). In the postcue, condition subjects generally perform poorly, as in regular change blindness experiments. However, in the retrocue condition, performance is hugely boosted (going from a capacity of three or four items for the postcue condition to six to 16 items for the retrocue condition), supporting the idea that IM and FM are much richer than is WM (Astle, Summerfield, Griffin, & Nobre, 2012; Griffin & Nobre, 2003; Landman et al., 2003; Murray, Nobre, Clark, Cravo, & Stokes, 2013; Pinto et al., 2013; Sligte, Scholte, & Lamme, 2008; Vandenbroucke, Sligte, Fahrenfort, Ambroziak, & Lamme, 2012). This suggests that IM and FM are less dependent on spatial attention than is WM. In the current investigation, we focus on FM, because previous research has suggested that it is dependent on cortical mechanisms (Sligte, Scholte, & Lamme, 2009) and therefore is possibly connected to consciousness, whereas IM may be partly based on a retinal afterimage (Sligte et al., 2008).

The notion that FM is independent of attention has already received some support by Vandenbroucke, Sligte, and Lamme (2011). When subjects performed an attention-demanding task concurrent with a VSTM task, for instance an N-back task or a task inducing an attentional blink, FM capacity was hardly affected, whereas WM capacity decreased. On average, WM capacity decreased significantly by around one or two items, whereas FM capacity was nonsignificantly reduced by half to one item. Although suggestive, Vandenbroucke et al.'s study investigated general task- and object-related attention rather than spatial attention. Of importance, spatial attention is thought to play a much more important role in visual processing (Yantis & Jonides, 1990). So, it could well be that the type of attention investigated by Vandenbroucke et al. does not impact VSTM very severely. Indeed, although the withdrawal of spatial attention is thought to completely erase WM (as shown by change blindness studies; e.g., Rensink et al. 1997), Vandenbroucke et al. found only a slight impact of attentional manipulations on WM capacity. Thus, this study did not resolve the fundamental question on the relation between *spatial* attention and VSTM.

In the current study, we investigated the reliance of VSTM on spatial attention in the following way. Subjects performed a change detection task (see Figure 2), using post- and retrocues as before. Crucially, to manipulate spatial attention, we added an attentional cue that appeared prior to the presentation of the memory array (the first screen). This additional *precue* indicated which location most likely would be the test location, as indicated by the subsequent retro- or postcue. The precue was 80% (in Experiment 1) or 75% (Experiment 2) valid, meaning that on some trials the precue did not predict the test location correctly. However, the retro- and postcue were always 100% valid. So, only the rectangle at the retrocued or postcued location could change orientation from memory to test display; none of the other rectangles could. Subjects were instructed to spatially attend to the precued location before the memory display was presented, because this cue would most likely indicate the location highlighted by the subsequent task-relevant retro- or postcue. The crucial analysis tested how well subjects performed the task when the precue was *invalid*; that is, when the precued, attended location did not correspond to the location tested with the subsequent retro- or postcue. We also used trials in which no precue whatsoever was presented, which served as a baseline condition.

Note that with a valid precue, the task becomes easy, and subjects can be expected to perform 100% correct (which they basically did). The interesting comparison is between the baseline condition without precue and the invalid precue conditions. How much memory capacity of either FM or WM would be lost when attention is diverted to another location? We therefore defined capacity loss as the number of items lost from memory when attention was diverted (invalid precue) compared to when attention was distributed spontaneously (no precue).

To preview our results, in all experiments we found that capacity loss was similar for the retrocue and postcue conditions when spatial attention was diverted (i.e., invalidly precued trials). This suggests that VSTM consists of two separable parts, FM-core and WM, and that only the latter requires focused attention. Together

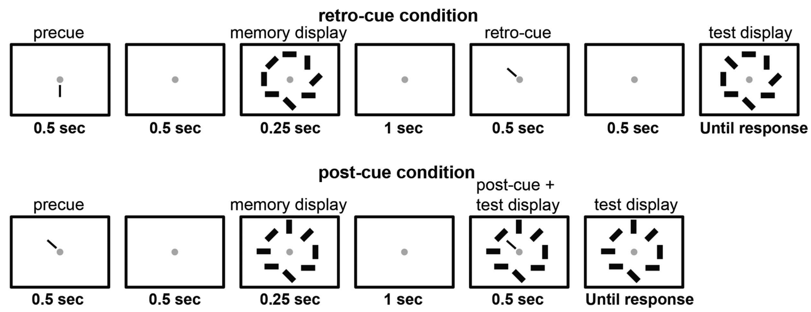

Figure 2. An overview of the retrocue and postcue condition in our experimental paradigm. The panels from the memory display onward depict the generic retro- and postcue conditions. In both conditions, the subject indicates whether the item at the cued location has changed. Yet, in the retrocue condition, the relevant information can be accessed before interfering visual information (the test display) has been presented. In the current paradigm, on a subset of trials, an initial precue (the leftmost panel) indicated at which location the critical test item would appear (75%–80% precue validity). Note that the retrocue or postcue was always 100% valid; that is, only the orientation of the rectangle at the retro- or postcued location could change from memory to test display. The top panels show an invalidly precued retrocue trial (the precue did not correctly indicate the test location); the bottom panels show a validly precued postcue trial (precued and test location are the same).

the two stores add up to a large capacity storage in the retrocue condition (which we call FM-total). Furthermore, in addition to objective performance, we also obtained subjective confidence ratings (Dienes & Seth, 2010; Overgaard, Timmermans, Sandberg, & Cleeremans, 2010). Generally, it is thought that if subjects provide correct answers but feel that they are guessing (low confidence), their performance may be based on unconscious information. However, if subjects are confident when they give correct answers and feel that they are guessing only when they give inaccurate responses, then the information underlying the performance is thought to be consciously available (Merikle, 1992; Pasquali, Timmermans, & Cleeremans, 2010). Crucially, Experiment 2 showed that minimally attended FM-core representations yielded not only correct performance but also high confidence on correct and low confidence on incorrect trials. This suggests that minimally attended FM-core representations can be used for correct decisions *and* yield conscious memories.

Experiment 1: Working Memory Is Erased When Spatial Attention Is Withdrawn, Whereas Fragile Memory Is Spared

In Experiment 1 we aimed to unveil how visual memory is affected when spatial attention is diverted. On most trials, subjects received a precue that indicated where they needed to attend. The critical test was how much memory declined when subjects were tested at a relatively unattended location.

Method

Subjects. In this experiment, 36 subjects (25 female; age range = 20–27 years, average age = 22.8 years), all having normal or corrected-to-normal vision, participated. All subjects gave their written informed consent to participate in the study, which was approved by the local ethics committee of the University of Amsterdam. In this and the subsequent experiments, the number of subjects was preplanned, and there were no additional stopping or continuation rules. In all Experiments 13–36 subjects were tested, because previous studies (Pinto et al., 2013; Sligte et al., 2008; Vandenbroucke et al., 2011) suggested that this sample size is large enough for reliable measurements.

Stimuli and procedure. Subjects performed a change detection task in which they indicated whether the object at the cued location was the same across memory and test display. Both the memory and test display consisted of eight oriented white rectangles (size in visual angle: 1.16° × 0.29°; four possible orientations: oblique [45° or 135°], vertical or horizontal) on a black background. Individual rectangles were evenly distributed on an imaginary circle (radius 4.68°) around fixation. The cue consisted of a 3-pixel yellow line: at one end close to fixation, and at the other end close to the location of the rectangle. The experiment consisted of 15 blocks of 40 trials. In all blocks except three (Blocks 4–6), a precue appeared, indicating with 80% validity where the test cue would appear. Subjects were aware of the overall precue validity and were instructed to employ the precue. The precue was similar to the test cue but colored blue.

In the retrocue condition, we measured VSTM capacity before visual interference (or FM-total capacity). The postcue condition assessed VSTM capacity after visual interference (or WM capacity). In both cases the cue appeared 1 s after offset of the memory display and was visible for .5 s. The precue was presented for .5 s (followed by a .5-s blank), the memory display for .25 s, and the test display remained visible until response. No-precue and precue trials were presented in different blocks; otherwise all trials were randomly intermixed. Therefore, subjects did not know beforehand whether the precue was valid or invalid, or whether the subsequent cue would be a retrocue or a postcue.[1]

[1] IM trials (where the retrocue appears 100 ms after offset of the memory display) were added because pilot studies have suggested that this enhances usage of the retrocue and thus improves the quality of the data. However, performance on IM trials, unlike on FM trials, may be partially driven by afterimages (Sligte, Scholte, & Lamme, 2008). Therefore, we do not include the results of the IM trials in the Results section of this experiment or the subsequent ones. Note, however, that the results of the IM trials were nearly identical to the results of the FM trials.

Prior to the experimental sessions, all subjects performed a training session of the change detection task (480 trials) without precues. Subjects were excluded if their average percentage correct on all trials combined was less than 75%. This resulted in the exclusion of three (out of 39) subjects. We added the training session because previous studies in our lab have suggested that although fragile memory may be formed automatically, the readout of fragile memory requires subjects to learn to use the retrocue. Without training, many subjects may simply start ignoring the retrocue and thus not employ fragile memory at all. Thus, we argue that without training, the obtained data may be uninformative about fragile memory. Note that when high-contrast stimuli are used and iconic memory (Sperling, 1960) is measured, this is less of an issue, because performance may then largely rely on afterimages (Sligte et al., 2008), which are easy to employ (subjects simply report what they still see in front of them).

Data analysis. For the dependent variable for our analysis in this and the following experiments, we used capacity (number of items remembered from the first array), which was calculated from the task performance as follows (Cowan, 2001): capacity = (hit rate + correct rejection rate − 1) × memory set size. We investigated both absolute and relative capacity loss as a function of attention and memory condition. We defined *absolute capacity loss* as the difference between capacity on the trials without a precue and capacity on the invalidly precued trials. Absent (rather than valid) precue trials were used as the baseline for two reasons. First, on validly precued trials, subjects needed to memorize only one item leading to near ceiling performance, which makes it an uninformative baseline. Second, our research question focuses on how attentional withdrawal impacts *general* VSTM, not VSTM when only one item has been attended. To assess significance of the absolute capacity loss, we performed a two-way analysis of variance (ANOVA) with independent variables cue type (absent or invalid) and memory condition (retrocue or postcue) and dependent variable capacity.

In addition to absolute capacity loss, *relative capacity loss* was investigated. We defined *relative capacity loss* in the retrocue condition as absolute capacity loss in the retrocue condition minus absolute capacity loss in the postcue condition. We used *relative capacity loss* to distinguish between the two models sketched in Figure 1. In the postcue condition, only WM would be available, so any capacity loss would equal WM capacity loss. Concerning the retrocue condition, our prediction was that if WM and FM-core were separate (the two-component model; see Figure 1) and that if FM-core did not depend on attention, then capacity loss in the retrocue condition would equal capacity loss in the postcue condition; in other words, relative capacity loss would be zero. However, we predicted that if FM-core did depend on attention, then a relative capacity loss would be larger than zero. Our prediction was also that if, on the other hand, WM and FM-core coincided (the one-component model; see Figure 1) and if FM did not depend on attention, then absolute capacity loss in the retrocue condition would be zero and relative capacity loss would be negative (in the amount equal to WM capacity). Finally, we predicted that if in this model FM-core did depend on attention, then there would be a relative capacity loss somewhere between zero and set size, depending on the effect of attention on FM-core (see Table 2).

For assessing significance regarding relative capacity loss, the same ANOVA was performed as before, but now the dependent variable was relative capacity loss rather than absolute capacity loss. Furthermore, to assess null results, we applied Bayesian analysis with a JZS prior (Rouder, Speckman, Sun, Morey, & Iverson, 2009), which reveals evidence for the alternative hypothesis, or the null hypothesis (Bayes factor [BF] < 1: evidence for rejecting the null hypothesis; 1–3: anecdotal evidence for the null hypothesis; 3–10: substantial evidence for the null hypothesis; >10: strong evidence for the null hypothesis; Jeffreys, 1961; Wagenmakers, Wetzels, Borsboom, & Van Der Maas, 2011).

Results

To investigate the effect of attention on FM and WM, we assessed capacity loss on invalidly precued trials compared to no precue trials. Absolute capacity loss was similar for the retrocue and postcue conditions (retrocue: 2.2; postcue: 1.7; see Figure 3 and Table 3), relative capacity loss was higher for the postcue than the retrocue condition (retrocue: 0.5, postcue: 1.7; retrocue relative capacity loss did not significantly differ from zero). Precue valid trials were not further analyzed, but note that performance on these trials was nearly perfect (retrocue, valid precue: 96.4% correct; postcue: 93.2% correct) and significantly better than on no precue and invalid precue trials, $F(2, 70) = 235.5$, $p < .001$, $\eta^2 = .87$.

Both the idea that spatial attention works as a spotlight (Eriksen & St. James, 1986; Posner & Petersen, 1990) and the notion that attention has a gradient distribution (LaBerge, 1983; LaBerge & Brown, 1986; LaBerge, Carlson, Williams, & Bunney, 1997) suggest that as distance between precued and tested location increases, capacity loss should increase as well. To test these views, we redid these analyses, but now we included only three out of seven of the invalidly precued trials where the distance between the invalidly precued location and the test location was largest (see Figure 3). We found similar results but now with overall larger capacity

Table 2
Absolute and Relative Capacity Loss, Depending on the Effect of Attention on FM-Core and the Architecture of VSTM

Model	Attention effect	Absolute capacity loss postcue	Absolute capacity loss retrocue	Relative capacity loss
FM-core and WM separate	FM-core not affected by attention	WM capacity	WM capacity	0
FM-core and WM coincide	FM-core not affected by attention	WM capacity	0	Minus WM capacity
FM-core and WM separate	FM-core affected by attention	WM capacity	Between WM capacity and set size	Between 0 and set size minus WM capacity
FM-core and WM coincide	FM-core affected by attention	WM capacity	Between 0 and set size	Between WM capacity and WM capacity set size

Note. VSTM = visual short-term memory; FM = fragile memory; WM = working memory.

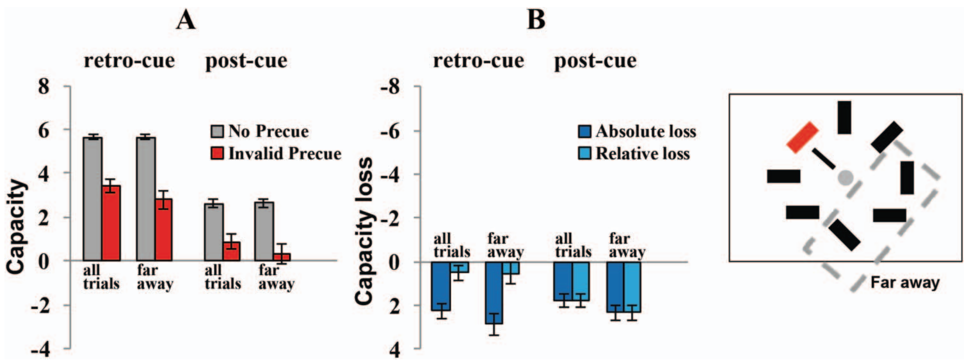

Figure 3. An overview of the results of Experiment 1. Baseline capacity (no precue) is higher in the retrocue condition than in the postcue condition (Panel A). When spatial attention is diverted (invalid precue), the absolute drop in capacity is similar for both retro- and postcue conditions, and increasing the distance between the invalidly precued and tested location increases the drop in memory capacity. It is important to note that the absolute drop in capacity is the same for the retrocue and postcue conditions, so that the relative loss in capacity is larger in the postcue condition, because it is almost entirely abolished, whereas the relative loss in the retrocue condition is nearly zero (Panel B). Error bars indicate standard error of the mean. See the online article for the color version of this figure.

losses (absolute losses, retrocue: 2.8; postcue: 2.3; relative capacity loss, retrocue: .5; postcue: 2.3; retrocue relative capacity loss not significantly different from zero). It is interesting that on these trials, postcue capacity was .29, which was not significantly different from zero, indicating that all WM capacity was lost when attention was diverted far away.

In addition to capacity results, the accuracy results, hit rates, and false alarms are reported in the online supplemental materials for this and the subsequent experiments. Furthermore, we investigated the idea that after a longer sequence of validly precued trials, attention is more focused on the precued location, and thus performance on the invalidly precued location is diminished. Thus, we analyzed whether the number of preceding validly precued trials affected performance on an invalidly precued trial. We found that for both experiments this did not significantly affect the results; the results of these analyses can also be found in the online supplemental materials.

The results of Experiment 1 are compatible with the first row of results we predicted in Table 2; that is, that the model sketched in Figure 1A is correct (FM-core and WM are separable) and that FM-core is not dependent on spatial attention. The results could also be compatible with the fourth row of predictions; that is, that FM-core and WM coincide and that FM does depend on attention. However, it is rather unlikely that this is the case, because this hypothesis predicts a rather broad range of potential results (relative capacity loss being between WM capacity and WM capacity, which is set size), whereas we found relative capacity loss to be exactly zero.

Note that we found that the results of Experiment 1 generalize across different degrees of attentional diversion. In a follow-up experiment (see the online supplemental materials for details), we found that varying overall precue validity (from 0% to 75%), which induced more or less distraction of attention, still produced the same pattern of results. Across different precue validities,

Table 3
Overview of the Results of Experiment 1

Variable	$F(dfs)$	$t(df)$	p	η^2	Cohen's d	Bayes factor
Initial experiment						
Absolute capacity loss, all distances	$F(1, 35) = 1.35$		.25	.04		3.01
Relative capacity loss, all distances	$F(1, 35) = 4.55$		.04	.12		.75
Relative capacity loss retrocue vs. 0		$t(35) = 1.16$	.25		.23	3.01
Main effect of distance precued-tested on capacity loss	$F(1, 35) = 10.4$		.003	.23		.078
Absolute capacity loss, farthest away	$F(1, 35) = 1.17$		.29	.03		3.26
Relative capacity loss, farthest away	$F(1, 35) = 6.4$		.016	.15		.35
Relative capacity loss retrocue vs. 0		$t(35) = 1.08$	.29		.2	3.26
Postcue capacity vs. 0		$t(35) = .98$	.33		.16	3.58
Follow-up experiment						
Absolute capacity loss all precue validities	$F(1, 26) = .044$		.84	.002		4.81
Absolute loss, highest precue validity	$F(1, 26) = .23$		.64	.01		4.42
Relative loss, highest precue validity	$F(1, 26) = 3.62$		.068	.12		1.03
Relative loss retrocue vs. 0		$t(26) = .48$	.64		.05	4.42

absolute capacity loss was similar in the retrocue and postcue conditions, and relative loss in the retrocue condition was indistinguishable from zero. Again, this supports the idea that VSTM consists of two separable components and that of these only WM is erased when attention is withdrawn.

In Experiment 1, the number of to-be-remembered objects was the same in the retrocue and postcue conditions. Thus, baseline accuracy (no precue trials) was higher in the retrocue condition than in the postcue condition. Therefore, an alternative explanation for the observed results is that withdrawing attention simply impacts a difficult task (the postcue condition) more than it impacts an easy task. Another question that is unanswered by Experiment 1 is whether the correct responses to relatively unattended objects are based on conscious knowledge or based on "blindsight"-like processes (Weiskrantz & Carey, 1998). The latter idea is in line with claims that change detection can be driven by implicit perception (Ball & Busch, 2015; Williams & Simons, 2000; but see also Mitroff, Simons, & Franconeri, 2002). If relatively unattended stimuli evoke only implicit memories, then correct responses on invalidly precued trials should be accompanied by the feeling that one is guessing (i.e., low confidence). In Experiment 2, we addressed both of these issues.

Experiment 2: Higher Accuracy and Higher Confidence for Minimally Attended Retrocue Than Minimally Attended Postcue Trials After Controlling for Task Difficulty

To equate task difficulty, we staircased performance at 75% correct across memory conditions by adjusting the set size of the memory display when no precue was presented. When accuracy exceeded 75%, an item was added, whereas when it dropped below 75%, an item was subtracted. If VSTM consists of two separable parts (see Figure 1A), FM-core and WM, with only the latter strongly depending on attention, then staircasing should not affect the basic pattern of results. Again, WM should be erased by attentional withdrawal, but FM-core should be unaffected, leading to the same absolute loss for the retrocue and postcue conditions (and thus zero relative loss in the retrocue condition). Alternatively, if the results of Experiment 1 are driven by differences in baseline task difficulty, then the pattern of results should alter. Because the retrocue condition has a higher baseline capacity, this would result in a higher absolute capacity loss (and a nonzero relative loss) compared to in the postcue condition.

We investigated, in addition to staircasing baseline task difficulty, confidence of memory judgments by having subjects wager points after each trial (Persaud, McLeod, & Cowey, 2007). We assessed confidence because of the presumed link between metacognition and conscious experience (Lau & Rosenthal, 2011). The reasoning is that when one has a conscious experience, this is generally accompanied by the knowledge, or metacognition, that one has access to the contents of this experience (Rosenthal, 2000). Vice versa, if information is processed without evoking a conscious experience, metacognition is absent as well, as dramatically illustrated in the case of blindsight (Weiskrantz & Carey, 1998). However, note that this line of reasoning is not uncontroversial (Reder & Schunn, 1996) and that metacognition may be accurate, even given chance performance (Scott, Dienes, Barrett, Bor, & Seth, 2014).

Assuming a link between accurate metacognition and conscious experiences, we reasoned as follows. If minimally attended memory were based on implicit processing, then a blindsightlike situation should occur. Subjects could give correct answers when spatial attention is diverted, yet they should feel like they are guessing. In that case, both for minimally attended retrocue and postcue trials, confidence should be uniformly low for both correct and incorrect answers. However, if conscious memories arise even with minimal attention, then confidence should be higher for correct than incorrect responses. This should especially be the case in the retrocue condition, where capacity is higher in the minimally attended situation. Note that the current analysis does not focus on meta-d' (Barrett, Dienes, & Seth, 2013), partly because performance in the baseline condition is staircased but also partly because there are too few trials in the unattended conditions to provide a reliable meta-d' measure. However, we report, in addition to confidence results, confidence results as a function of accuracy in the online supplemental materials.

Method

Experiment 2 was the same as Experiment 1 except for the following changes.

Subjects. In this experiment, 36 subjects participated (29 female; age range = 18–24 years, average age = 20.4 years). In the main experiment, subjects could increase or decrease their reward (standard reward was 1 credit or 10 euros per hour) by betting points on their answers. At the end of the experiment, these points were converted to a monetary compensation (1,000 points translated to 1 euro). On average, this led to an additional payment of two euros per subject for the entire experiment.

Stimuli and procedure. Set size per memory condition was staircased using the baseline blocks (precue absent), so that accuracy was kept at 75% correct separately for retrocue and postcue trials. When performance exceeded 75%, one rectangle was added to the memory and test displays, whereas one rectangle was removed if performance dropped below 75% (see Figure 4 for placement of the rectangles). After the staircasing procedure of 12 blocks of 48 trials, subjects returned on a separate day for a second session of 18 blocks of 48 trials. This session consisted of 10 precue blocks (where each trial was preceded by a precue with 75% overall validity), intermixed with eight precue absent blocks, of which four were used for additional staircasing (to adjust the baseline to any learning that could occur during the experiment). Staircasing was done on the precue absent blocks so that baseline difficulty was the same across memory conditions. Thus, if we now found a lower accuracy (and similar absolute capacity) loss in the retrocue than in the postcue condition, this could not be due to differences in task difficulty. In all conditions, at the end of each trial subjects wagered 1–4 points to indicate how confident they were about their decision. There was no time limit on their wager decision. After pacing their wager, subjects received feedback indicating whether their change detection answer was correct and how many points they had earned or lost.

Results

See Figure 5 and Table 4 for an overview of the results. On valid precue trials, performance was higher than on invalid and absent

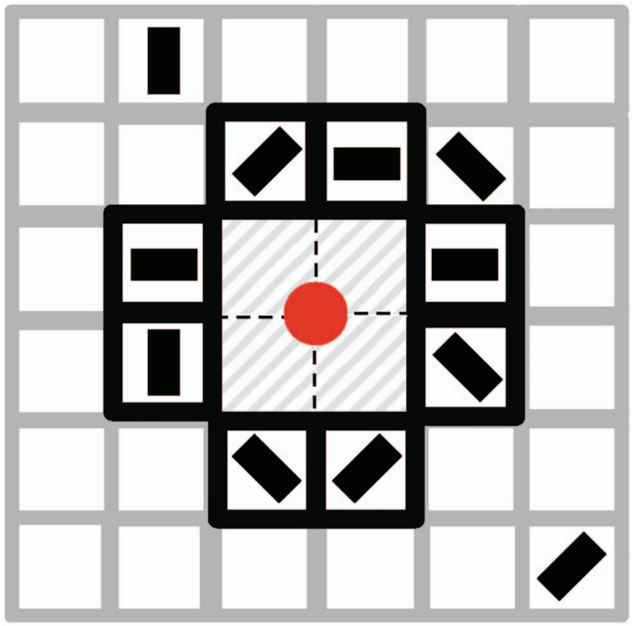

Figure 4. An overview of the placement of objects in Experiment 2. Items were placed in an imaginary grid (which was not visible during the experiment). The four inner cells were kept empty. The first eight items were placed in the remaining cells that were closest to fixation (here depicted in bold). Beyond set size eight, items were randomly placed in any of the remaining cells. See the online article for the color version of this figure.

precue trials and was nearly perfect, $F(2, 70) = 497.4$, $p < .001$, $\eta^2 = .93$; retrocue: 98.8% correct; postcue: 97.8% correct), indicating that subjects employed the precue to focus spatial attention. Accuracy on no-precue trials did not differ significantly across memory conditions (retrocue: 75.6%; postcue: 75.8%), indicating that our staircasing procedure succeeded in equalizing task difficulty. Note that this equal task difficulty was obtained for different set sizes for retrocue and postcue trials (average set size, retrocue: 14.8; postcue: 9.4). Crucially, even with matched task difficulty, we replicated the main findings of Experiment 1. Again, absolute capacity loss was similar for the invalidly precued retrocue and postcue conditions, and relative capacity loss was larger for the invalidly precued postcue than for the retrocue condition (absolute loss, retrocue: 1.68; postcue: 2.37; relative loss, retrocue: −.69; postcue: 2.37; retrocue relative loss not significantly different from zero).

We performed a second analysis, but this time we included only the 42.9% (approximately three out of seven) of trials where distance between precued location and test location was largest. Although overall capacity loss was higher in this case, again absolute capacity loss was similar for the retrocue and postcue conditions (retrocue: 2.58, postcue: 2.76), and relative capacity loss was higher for the postcue condition (retrocue: −.18; postcue: 2.76). Again, retrocue relative loss was not significantly different from zero, showing that increased attentional distraction did not alter the pattern of results. Thus, both analyses replicated the findings of Experiment 1. This supports the two-component model of VSTM (see the first row of predictions in Table 1) and suggests that differences in task difficulty cannot explain the findings of Experiment 1.

Confidence. For a complete overview of the confidence results and for confidence results as a function of performance, see the online supplemental materials. We compared invalidly precued retrocue trials to invalidly precued postcue trials. This revealed a higher confidence for correct retrocue trials and a lower confidence for incorrect retrocue trials (confidence difference correct minus incorrect, retrocue vs. postcue), $t(35) = 2.98$, $p = .0052$, $d = 1.5$ (see Figure 5). These results suggest that the increase in correct, minimally attended, trials in the retrocue condition is not due to blindsightlike processes, because in that case confidence for correct trials should be lower for retrocue than for postcue trials. Thus, relatively unattended information in the retrocue condition seems to generate conscious visual memory. Note that it is possible that unattended FM representations are always conscious. Yet, it could also be that FM representations are initially unconscious and

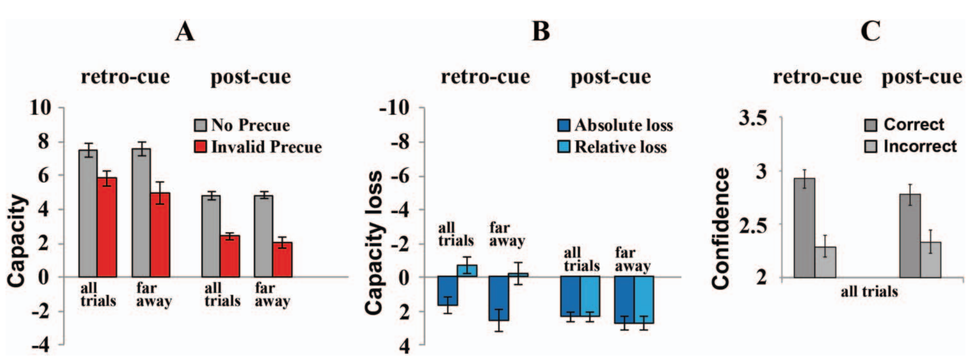

Figure 5. An overview of the results of Experiment 2. Even after staircasing task difficulty, the pattern of results was the same as in Experiment 1. Absolute capacity loss was similar for the retrocue and postcue conditions (Panel A), for all trials and for the trials in which the invalidly cued item was farthest away (Panel B). Panel C shows the confidence results for invalidly precued trials. Confidence on correct trials was higher for invalidly precued retrocue trials than for invalidly precued postcue trials. Error bars indicate standard error of the mean. See the online article for the color version of this figure.

Table 4
Overview of the Statistical Results of Experiment 2

Variable	$F(dfs)$	$t(df)$	p	η^2	Cohen's d	Bayes factor
Accuracy, precue absent trials		$t(35) = .08$	.94		.15	5.57
Absolute capacity loss, all distances	$F(1, 35) = 1.61$		.21	.04		2.67
Relative capacity loss, all distances	$F(1, 35) = 84.1$		<.001	.34		$<1 \times 10^{-8}$
Relative capacity loss retrocue vs. 0		$t(35) = 1.27$	.21		.27	2.67
Main effect of distance precued-tested on capacity loss	$F(1, 35) = 6.87$		.013	.16		.29
Absolute capacity loss, farthest away	$F(1, 35) = .05$		.83	.001		5.46
Relative capacity loss, farthest away	$F(1, 35) = 7.29$		.011	.17		.25
Relative capacity loss retrocue vs. 0		$t(35) = .22$	.83		.01	5.46

that they are lifted into consciousness only after the retrocue has been employed (Sergent et al., 2013).

Although Experiment 2 provides evidence that unattended FM representations yield accurate metacognition, it has two important drawbacks. First, we used betting as a way to measure confidence, yet, because of risk aversion, this method may distort confidence measurements (Dienes & Seth, 2010; Konstantinidis & Shanks, 2014). Second, subjects received feedback after each trial. This may have trained subjects to recognize in which conditions their performance was more accurate. Again, this may have skewed the assessment of confidence. Therefore, we performed an additional experiment in which we replicated Experiment 2 but without having subjects bet points; rather, they simply indicated how confident they felt on a trial-by-trial basis. Moreover, subjects received no feedback on their performance. The results of this experiment are essentially the same as those of Experiment 2 (see the online supplemental materials information for an extensive description). Again, absolute capacity loss was similar in the retrocue and postcue conditions, and relative loss in the retrocue condition was not significantly different from zero. The results hold when we look at only those trials where distance between attended and tested location is largest. Moreover, in that condition, capacity in the postcue condition was not significantly different from zero. Finally, in both the retrocue and postcue conditions, we again found relatively accurate metacognition for unattended trials (higher confidence for correct than incorrect answers).

Thus, this replication confirms the results of the previous experiments that withdrawal of focused attention affects memory capacity in the postcue condition more than in the retrocue condition. Further, the confidence results confirm the notion that even with minimal attention conscious memories are formed.

General Discussion

In two experiments, supplemented by several control experiments, we investigated the relation between spatial attention and visual short-term memory (VSTM). In all experiments, we found that working memory (WM) was almost completely erased when spatial attention was diverted via an invalid precue. In the retrocue condition, used to measure fragile memory (FM) capacity, we found effects of diverting attention that were entirely compatible with the model (sketched in Figure 1A) that VSTM consists of an attention-independent FM-core component and a separate attention-dependent WM component. Altogether, our results suggest that FM-core, which is available for long time periods of time (up to ~3 s) prior to visual interference, requires only minimal attention and supports conscious visual memory.

Previous Manipulations of Attention in VSTM

Our current results are in line with, and extend, earlier research into the dependence of FM/FM-core on attention. Vandenbroucke et al. (2011) found that general, task-related attention (e.g., concurrently performing an N-back task) had little impact on FM. To investigate the role of attention during recall, Landman et al. (2003) tested how presenting an invalid retrocue impacted FM. In their setup, subjects were presented, on some trials, with two retrocues, and they had to report whether a change had occurred on the location indicated by the second retrocue only. Landman et al. found that performance with two retrocues was similar to performance with one retrocue, suggesting that initial misdirecting of attention during recall had little impact on FM (but see van Moorselaar, Olivers, Theeuwes, Lamme, & Sligte, 2015). Note that a crucial difference between these studies and the current one is that neither previous study tested spatial attention during encoding. This is pivotal because other studies have suggested that visual processing is more sensitive to spatial attention than are other types of attention, such as feature-based attention. For instance, a study by Yantis and Jonides (1990) showed that spatially focusing attention on one location prevents attentional capture by salient objects at other locations, whereas featural attention cannot prevent either spatial or featural capture of attention (Theeuwes, 1992, 2004).

In contrast with the studies by Vandenbroucke et al. (2011) and Landman et al. (2003), which found that withdrawing attention had little effect on FM, Persuh, Genzer, and Melara (2012) claimed evidence that attentional diversion (by performing a concurrent visual search task) severely impacted iconic memory (IM). However, in Persuh et al.'s experiments, subjects were not trained on using a retrocue, so it is unclear how much they were able to employ IM (as evidenced by the fact that Persuh et al., 2012, found an IM baseline capacity of five to six items, well below the normally found IM capacity of eight or higher; e.g., Sligte et al., 2008). Moreover, no WM condition was added, so it is unclear how much their attentional manipulation affected IM and how much it affected WM. Indeed, in both their experiments, attentional diversion led to a capacity drop of approximately four items, which resembles WM capacity. Thus, Persuh et al.'s attentional manipulations may in fact have had the same effect as our current manipulations of erasing WM but leaving FM-core (or in their case IM-core) untouched.

Another set of intriguing studies into the dependence of IM on attention was conducted by Mack, Erol, and Clarke (2015; Mack, Erol, Clarke, & Bert, 2016). In the latter study, subjects performed a dual task in which they either reported whether four peripherally located bisected circles were all the same or they reported the identity of six, more centrally placed letters. After disappearance of the memory display, subjects received a cue indicating which task they had to perform. In the experimental condition, subjects were cued to perform the circle task on 90% of the first 90 trials, as well as on Trials 91–100. Thus, on the critical 101st trial they were strongly induced to attend to only the peripherally placed bisected circles. In their first experiment Mack et al. (2016) found that when no letters were presented on the critical 101st trial, eight out of 15 subjects did not notice this. In their second experiment, on the critical 101st trial, the centrally placed letters were horizontally or vertically rotated, yet seven out of the 10 tested subjects did not notice this.

As in Persuh et al.'s (2012) study, subjects were not trained on the use of a retrocue, so it is not completely clear how well they employed their iconic memory—baseline capacity in the single-task condition, where only the central letters had to be recalled, indicated an IM capacity of four items. And again, because there was no WM condition and no reliable measure for the quantitative drop in capacity (due to the limited number of critical test trials), it cannot be determined whether the absolute loss in capacity in the IM condition would have exceeded absolute capacity loss in the WM condition. Thus, again it is possible that the attentional diversion in Mack et al.'s (2015, 2016) investigations had the same effect as in our current research of erasing WM but leaving IM/FM-core untouched.

New Model of VSTM

An important implication of the current findings is that they suggest a novel understanding of VSTM. One can think of VSTM as consisting of two separable processes that retain different information. One is FM-core, which is relatively independent of spatial attention yet is entirely erased when interfering visual information is presented. The other is WM, which is not affected by visual interference yet is critically dependent on spatial attention. Thus, when a visual scene is viewed, minimally attended objects are stored in FM-core, and fully attended ones in WM. Subsequently, when a new visual scene appears, FM-core is entirely erased, yet WM persists.

Crucially, the findings of Experiment 2 revealed that relatively unattended memory representations can produce high confidence memories. This suggests that both FM-core and WM support conscious contents, which is in line with previous findings on metacognition for FM (Vandenbroucke et al., 2014).

Although the current data are congruent with a two-component model of VSTM, this is not the only possible explanation. Earlier work by Sligte, Wokke, Tesselaar, Scholte, and Lamme (2011) found that transcranial magnetic stimulation applied to the dorsolateral prefrontal cortex reduced capacity in the postcue condition (by one item) but did not affect capacity in the retrocue condition. Also, Vandenbroucke et al. (2011) found a significantly higher decrease in capacity in the postcue than in the retrocue condition as a result of attentional withdrawal. These findings seem difficult to reconcile with the notion that VSTM consists of two separable components. An alternative explanation, as sketched in Table 2, is that some items are doubly represented in both FM-core and WM but that the impact on FM-core depends on which type of attention is manipulated. Perhaps FM-core is dependent on only spatial attention and not on the type of attention manipulated by Sligte et al., and Vandenbroucke et al. (and hence they found no significant capacity loss in the retrocue condition). This differential dependence on various types of attention could be due to spatial attention's affecting visual processing at an earlier stage than do other types of attention (Maunsell & Treue, 2006; Theeuwes & Van der Burg, 2007).

Thus, the data are not entirely conclusive as to how the different components of VSTM are related to each other. It is clear, though, that WM is more dependent on spatial attention than is FM. When stimuli are minimally attended, WM is almost entirely erased, yet FM remains largely intact.

Spotlight or Gradient Model of Attention

The current results support, in addition to impacting our understanding of VSTM, the gradient model of attention (LaBerge, 1983; LaBerge & Brown, 1986; LaBerge et al., 1997). In both experiments, capacity loss increased as distance to the attended location increased. Moreover, in both experiments (and especially Experiment 2) there seemed to be some residual attention even at the locations farthest away from the focus of attention. This supports the central claim of the gradient model of attention that spatial attention does not have sharp boundaries but drops off gradually.

Consciousness

An important question in consciousness research is whether consciousness requires attention (Cohen & Dennett, 2011; Koch & Tsuchiya, 2007; Lamme, 2003). According to the influential global workspace theory (Baars, 1988, 2005; Dehaene & Naccache, 2001), only information that gets selected and is then broadcasted throughout a distributed "neuronal global workspace" gains conscious access. Generally, attention is seen as the necessary mechanism for selection and broadcasting (Baars, 2002).

Contrasting with global workspace is Block's distinction between phenomenal and access consciousness (Block, 2005, 2011) and Lamme's recurrent processing theory of consciousness (Lamme, 2004, 2006; Lamme & Roelfsema, 2000). Both theories claim that attention is not required for phenomenal or visual consciousness but only for later stages of consciousness (access or cognitive consciousness).

Because it seems implausible that unconsciously perceived stimuli can evoke conscious memories, VSTM has been interpreted as a (conservative) proxy measure of visual consciousness (for instance, in masking studies where conscious recall is seen as proof of conscious perception; e.g., Marcel, 1983). The original *change blindness* phenomenon has been widely interpreted as revealing that the apparent richness of visual awareness is illusory and that visual awareness is dependent on attention (Baars, 2005; Cohen & Dennett, 2011; Dehaene, Changeux, Naccache, Sackur,

& Sergent, 2006; Noë, 2002; O'Regan & Noë, 2001). Crucially, the current findings reveal that change blindness findings do not generalize to all stages of VSTM. Only WM, but not FM-core, is entirely dependent on attention. This suggests a distinction of consciousness and attention along the lines of the models of Block (2005, 2011) and Lamme (2004, 2006; Lamme & Roelfsema, 2000). It seems that there are (broadly speaking) two types of consciousness: a sensory part that is relatively independent of attention (as reflected in FM-core) and a cognitive part that is dependent on attention (WM).

Future Directions

The current research shows that varying degrees of attentional diversion all produce similar patterns of results: Withdrawal of spatial attention does not affect FM-core but diminishes WM. Yet, it is still possible that there is a critical cutoff point beyond which FM-core will be impacted by attentional withdrawal as well (which possibly drives the results of Persuh et al.'s, 2012, and Mack et al.'s, 2015, 2016, investigations). One way to test this is by presenting subjects with fully reliable precues with only one invalid precue trial at the end of the experiment. This invalid precue trial would be completely unexpected, and therefore the odds of any lingering spatial attention would be minimal. If under these circumstances there is still no effect of withdrawing spatial attention on FM-core and confidence for correct unattended retrocue trials is still high, then this confirms that conscious memories emerge even when spatial attention is completely absent.

Another interesting question is how the neural underpinnings of memory representations are shaped by spatial attention. Multivoxel pattern analysis (Norman, Polyn, Detre, & Haxby, 2006) applied to brain-imaging data can reveal whether, for instance, attended and unattended memories are stored similarly in early sensory areas but start to diverge in the parietal or frontal areas. This research may also reveal what the neural differences are between conscious, attended memories and conscious, unattended memories, thereby shedding further light on the fundamental issue of how consciousness and attention interact.

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