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Attending Object Features Interferes With Visual Working Memory Regardless of Eye-Movements

Zachary Hamblin-Frohman and Stefanie I. Becker
The University of Queensland

There is currently a debate about the relationship between feature-based attention (FBA) and visual working memory (VWM). One theory proposes that the 2 constructs should be synthesized into a single concept (Kiyonaga & Egner, 2013). In this unified theory, VWM is defined as attention directed toward internal representations that competes with attention for a shared limited resource. Contrary to this account, it has been reported that only overt attention shifts (saccades), but not covert attention shifts, interfere with VWM (Tas, Luck, & Hollingworth, 2016). However, covert attention may only have required spatial attention, not FBA, so that the lack of interference may be because of the fact that spatial attention does not interfere with VWM. The current experiment varied feature versus spatial attention and overt versus covert effects upon VWM performance, as measured with a change detection paradigm. Results across three experiments show that memory interference arises when objects features are attended, regardless of whether attention was directed overtly or covertly. In a fourth experiment we show that attending spatial information interferes with spatial working memory, whereas attending feature information does not. These findings demonstrate a dissociation between spatial attention and VWM, which leaves unified concepts of FBA and VWM intact.

Public Significance Statement

To what extent is our ability to remember a visual object or scene linked to our ability to selectively attend to only one or a few visual objects? A previous study suggested that only eye movements but not attention is closely linked to memory. The current study challenges this view, by showing that the lack of interference could have been because of the kind of attention being involved (spatial attention, rather than feature-based attention [FBA]). This leaves open the possibility that FBA and VWM share common resources.

Keywords: visual working memory, feature-based attention, spatial attention, eye-movements

Visual feature-based attention (FBA) allows behavioral guidance and selection of relevant objects in a visual scene on the basis of their feature attributes (e.g., color or orientation; Carrasco, 2011). FBA is important in visual search, where the spatial locations of goal-related items is unknown and, thus, only target features can guide selection by enhancing the discriminability and resolution of the sought after feature (Carrasco, 2011). Recently, there has been a debate to what extent FBA is involved in visual feature-based working memory (VWM); the ability to retain visual information in the absence of perceptual stimulation. VWM is known to be a capacity-limited store of short-term information, dedicated to the retention of feature information (Cowan, 2010). Recent research has emphasized the role of attention in the active maintenance of information in VWM (Cowan, 2011).

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Zachary Hamblin-Frohman and Stefanie I. Becker, School of Psychology, The University of Queensland.

Correspondence concerning this article should be addressed to Zachary Hamblin-Frohman, School of Psychology, The University of Queensland, McElwain Building, St. Lucia, QLD 4072, Australia. E-mail: z.hamblinfrohman@uq.edu.au

State-based models of VWM propose that remembered items are maintained via two levels of activation, an active state where items can be maintained by an *internal focus of attention*, and a passive state where attention is not actively involved in the maintenance of VWM items (D'Esposito & Postle, 2015; Olivers, Peters, Houtkamp, & Roelfsema, 2011; Vandenbroucke, Sligte, & Lamme, 2011). In passives states visual memories are easily overwritten by new visual stimulation (Sligte, Scholte, & Lamme, 2008), while actively maintained items are more resistant to interference (Pinto, Sligte, Shapiro, & Lamme, 2013). Items can be moved between active and passive states by shifting the focus of attention to task-relevant items (Olivers et al., 2011). It is argued that the items receiving this active retention are selected according to the principles of Desimone and Duncan's (1995) biased competition model (Kiyonaga & Egner, 2014). The biased competition model proposes that as there are limited resources to conduct visual processing so that top-down goals (as prescribed by the task) determine which item will be selected for prioritized processing. That is, for VWM, the most task-relevant items will receive the focus of attention, whereas irrelevant or less important items are relegated to a passive state (Olivers et al., 2011). Retrocueing studies, for instance, illustrate the competitive nature of

VWM. In retro-cueing, an attentional cue is presented after a to-be-remembered memory display has been extinguished, to highlight a specific item held in VWM. The results typically show better memory performance for the cued item than noncued items held in VWM (Gunseli, van Moorselaar, Meeter, & Olivers, 2015; Maxcey-Richard & Hollingworth, 2013; Myers, Stokes, & Nobre, 2017; Schmidt, Vogel, Woodman, & Luck, 2002). Critically cues are delivered postmemory encoding, meaning that changes in resource allocations are dynamically updated during the retention period, representing the shift of the attentional focus within VWM.

A current question in the field is whether, and to what extent, FBA and VWM share cognitive resources, or whether the concepts may even refer to the same mechanism (Awh, Vogel, & Oh, 2006; Chun, 2011; Chun, Golomb, & Turk-Browne, 2011; Olivers, 2009; Rensink, 2002). Of note, Kiyonaga and Egner (2013) argued that the differences between attention and (active) working memory systems are negligible, and that they should no longer be considered separate systems. Kiyonaga and Egner (2013) propose a *unified theory of attention and VWM*. According to this view, attention can either be allocated to externally perceived items (to fulfil classical attentional functions), or can be directed internally to mental representations of items (to fulfil functions of working memory). Internal and external attentions both rely upon the same cognitive mechanism and tap into a shared capacity-limited resource, leading to competitive interactions between the two. The unified account predicts that when attention or working memory are at capacity and the limits of the shared cognitive resource are exceeded, a trade-off should occur such that working memory performance declines when attention is taxed or vice versa. In dual task designs, where a VWM and attention task are performed concurrently (such as a visual search or object recognition, presented in the retention period of the memory trial), bidirectional performance trade-offs are observed. Maintaining high memory loads can slow visual search (Woodman & Luck, 2004) and performing a visual search task can cause loss of memory information (Cocchini, Logie, Sala, MacPherson, & Baddeley, 2002; Woodman & Luck, 2010). This implies that there is competition, or an attentional bottleneck, between attention and VWM where finite resources are delegated between the two systems for optimized performance. According to unified theories, these trade-offs are attributed to shifts in the focus of attention. Items that match the top-down goals receive a larger allocation of resources and are, therefore, prioritized for the task while remaining items suffer.

Another compelling example of the interaction between working memory and attention is memory-driven attentional capture. While holding an object feature in memory (e.g., red) in a separate visual search an irrelevant distractor sharing features with the memory item (e.g., red distractor) will capture attention (Hollingworth, Richard, & Luck, 2008; Olivers, 2009; Olivers, Meijer, & Theeuwes, 2006; Soto, Humphreys, & Heinke, 2006). Alternatively, if the search target matches the maintained memory feature, search is facilitated (Soto, Wriglesworth, Bahrami-Balani, & Humphreys, 2010). The actively maintained information renders the memory-related distractor more attractive to top-down goals, capturing attention. According to the unified account, items held in (active state) VWM are within the focus of attention (Olivers et al., 2006), which is functionally identical to attending that item's features (Kiyonaga & Egner, 2013; Tsubomi, Fukuda, Watanabe, & Vogel, 2013). The unified account can also provide an explanation for retro cuing effects in VWM (e.g., Gunseli et al., 2015). The cued item receives a larger portion of attentional/VWM resources as it is competitively the most task-relevant item, whereas resources for noncued items are decreased. Conversely, when FBA is directed toward external objects, in search, memory items are overwritten or displaced as there are no longer sufficient resources for active maintenance. It is critical to note that, to observe this competitive interaction between FBA and VWM, the cognitive load exerted by an experimental task must reach the capacity limit of this common resource.

Despite the evidence in favor of the unified account, some studies failed to find the predicted trade-off between FBA and VWM, which suggests a dissociation of the systems. Woodman, Vogel, and Luck (2001) found that retaining several items in VWM did not decrease search efficiency in a subsequent visual search task. This suggested that the mechanisms used for visual search and VWM are different and this was used to argue against the close relationship between attention and VWM. However, in a subsequent study the same authors found that when the memory load was spatial instead of visual, search efficiency did decrease (Woodman & Luck, 2004). Woodman et al. (2001) reasoned that their serial search primarily required spatial shifts of attention (Woodman & Luck, 1999) and hence, that a spatial working memory load would be more likely to interfere than a typical, feature-based VWM load (that was used originally).

This brings into focus the critical factor of *domain-specific* attention and working memory systems. There is distinction between spatial and feature attentional processing, separating the two in both function and neural localization (de Haan & Cowey, 2011). Visual objects can be attended by tuning attention to their feature values or by selecting the spatial location they occupy, recruiting different neural pathways (Giesbrecht, Woldorff, Song, & Mangun, 2003). If active working memory is internally directed attention then it follows that there would also be domain-specific memory systems. Previous studies have found dissociations between spatial working memory and VWM, both with behavioral and neurological methods (Courtney, Ungerleider, Keil, & Haxby, 1996; Klauer & Zhao, 2004; Postle, Idzikowski, Sala, Logie, & Baddeley, 2006; Tresch, Sinnamon, & Seamon, 1993). Spatial working memory is selectively impaired by spatial tasks such as object tracking or serial visual search, while VWM is only impaired with FBA tasks such as object feature recognition (Cocchini et al., 2002; Postle et al., 2006). The state-based *sensorimotor recruitment theory* incorporates this view from a neurological perspective. Working memory is described as a property that emerges from recruitment of specific sensory areas via the sustained allocation of attentional resources to these systems (D'Esposito & Postle, 2015). In line with this view, neurological studies have shown that activation for continuously attending stimuli is the same as holding that information in working memory (Tsubomi et al., 2013). Specifically this allows memory activation to occur wherever attention is directed; be it spatial, visual, olfactory or tactile sensations (Postle, 2006).

Despite the evidence suggesting that attention and VWM share a similar (domain-specific) architecture and functions, some studies suggest that VWM and attention are functionally separate and independent. Tas et al. (2016) provided evidence against the unified view of FBA and VWM, by showing that only overt attention (i.e., saccades), but not covert attention shifts interfere with VWM performance. In their experiments, participants were asked to maintain a high memory load in VWM, and were presented with an additional peripheral secondary object (SO) in the retention period of the memory task. In the saccade condition, participants moved their gaze to the SO, whereas in the fixation block, participants maintained fixation (controlled with an eye tracker). The results showed memory impairments in the saccade conditions but not in the covert attention condition (when compared with a SO absent condition). Tas et al. (2016) proposed that saccades interfered with performance because VWM provides a storage system for maintaining transsaccadic stability. During a saccade all visual input is disrupted (Matin, 1974), and it has been argued that VWM is necessary to maintain a stable perceptual representation (Hollingworth et al., 2008). According to this theory, saccade target objects would always be automatically encoded into VWM to aid transsaccadic stability, whereas this is not necessary for covert attention shifts. Critically this separates the demands of FBA and VWM, implying that they do not represent the same mechanism.

There is, however, a potential alternative explanation of the results of Tas et al. (2016). As participants were not required to interact with the SO it is possible that the SO was only full attended in the overt attention condition. Before executing a saccade, covert spatial attention is first moved to the target location (Deubel & Schneider, 1996; Peterson, Kramer, & Irwin, 2004; Posner, 1980) and this obligatory coupling of saccades and attention renders it likely that the SO was attended in the overt attention condition. However, in the fixation condition there is the possibility that the SO features were not attended or processed to the same extent. Tas et al. (2016) used an onset stimulus for the SO, under the assumption that onset stimuli automatically capture attention (Jonides & Yantis, 1988). However, several subsequent studies have shown that under some circumstances onset stimuli do not always capture attention (e.g., Boot, Brockmole, & Simons, 2005; Du & Abrams, 2009). When a visual search array contains many stimuli (i.e., high perceptual load) an abrupt onset will not attract attention or interfere with a concurrent task (Cosman & Vecera, 2009, 2010; Du & Abrams, 2009; Lavie, 2006). It is possible that the high memory load in Tas et al. (2016) similarly prevented attention being captured by the task-irrelevant SO, preventing depletion of allocated memory resources.

Of note, Tas et al. (2016) did use a validity manipulation to ascertain that the SO had attracted spatial attention. However, there was no incentive for participants to attend to the features of the SO in the covert attention condition and hence, it is possible that only the location of the SO was attended. That is, it is possible that the true underlying difference between the saccade and fixation conditions was not eye movements, but attending to the SOs features versus spatial location. As discussed, working memory and attention seem both to be highly modal-specific, potentially explaining the lack of interference in the covert condition.

The aim of the current study was to further investigate the effects of overt and covert orienting on VWM when taking into account the distinction between FBA and spatial attention. The results of the study will show whether it is interference from saccadic demands (Tas et al., 2016), or FBA directed toward target features that provides competitive interference with VWM (Kiyonaga & Egner, 2013).

Experiment 1

Experiment 1 systematically varied the requirements to attend to the SO (spatial vs. feature), orthogonal to the requirements to make a saccade or attend covertly to the SO. As in Tas et al. (2016), we used a dual-task paradigm that consisted of a color change detection task to assess VWM performance, and a selection task in which participants had to overtly or covertly attend a SO. Critically a response was now required for the SO. In the feature attention condition, participants had to identify the shape of the SO, while in the spatial attention condition, participants were asked to identify the location of the SO (see Figure 1 for an example of the procedures).

If the hypothesis of Tas et al. (2016) is correct, that saccade targets are automatically encoded into VWM to maintain transsaccadic stability, then VWM interference would be expected only in the saccade (overt) conditions, across both spatial and feature attention conditions, and not in any of the fixation (covert) conditions. If, on the other hand, the failure to find interference in the fixation condition was because of the fact that spatial working memory and VWM constitute separate modalities and only interact with the corresponding attentional counterpart, then VWM interference should occur in both saccade and fixation conditions for the FBA condition, but not in the spatial attention condition. Interference would also be expected in the spatial saccade condition, because saccades

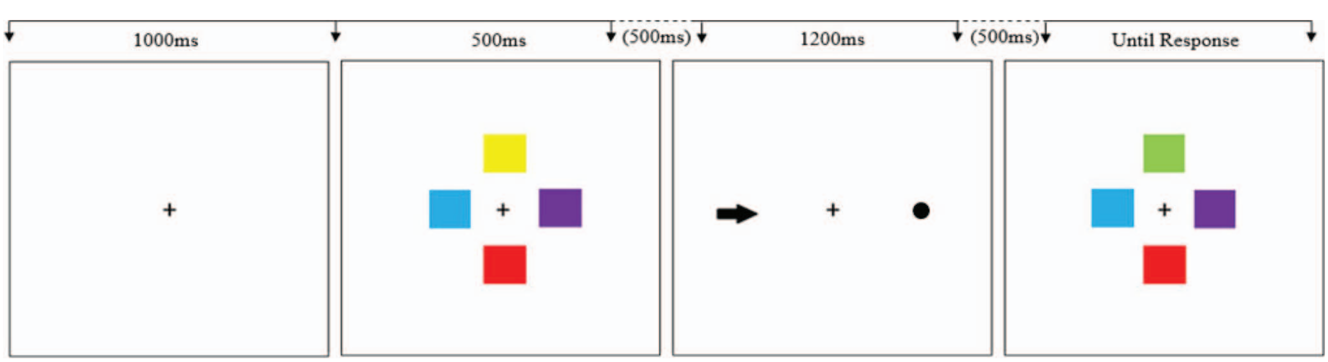

Figure 1. Trial structure in Experiment 1. After fixation participants would first memorize the array, then respond to the secondary object (feature trial is displayed on the left, spatial on the right) with or without making a saccade and finally make a same or different judgment to the test array. See the online article for the color version of this figure.

are preceded by an obligatory shift of attention to the saccade target location (e.g., Deubel & Schneider, 1996); however, this interference would not be because of the saccade itself, but to the attention being deployed to the SO. A corresponding result would argue against the claim that only overt selection leads to VWM encoding, and instead demonstrate that VWM and FBA are modality-specific, with separate resources for different modalities (spatial, features), but shared resources within a given modality (Kiyonaga & Egner, 2013; Postle, 2006). The key condition in Experiment 1 separating the two predictions is, thus, the FBA fixation condition, as it provides a measure of covert attention to the SO features without saccadic demands.

Method

Participants. Twenty-five participants (12 female) undergraduate students from the University of Queensland participated in this study for course credit and were included in data analysis. The sample size was determined based on the effect size of the interference effect ($d = \sim.675$) observed from the SO in Tas et al. (2016). We took a conservative estimate of this ($d = \sim.6$) and to achieve an appropriate power of $>.8$, with a criterion of .05, G*Power software (Faul, Erdfelder, Buchner, & Lang, 2009) computed a suggested sample size of 24. Mean age was 21.3 years ($SD = 6.35$) and all reported normal or corrected-to-normal vision. Thirty-two participants were originally tested; however, 7 were excluded, 4 for being unable to control their gaze (>25% invalidated trials), such as not being able to maintain fixation in fixation blocks, 2 for incorrectly responding to the SOs, that is, responding to spatial information in the feature condition, and 1 for scoring below chance. Study approval was granted by the University of Queensland's Faculty of Psychology Ethics Board.

Apparatus. Stimuli were presented on a 21-in. CRT monitor (refresh: 85Hz). Participants' heads were held in a constant position 600 mm from the screen by a chin and head-rest. Gaze location was measured by an SR-Research Eyelink-1000 eye tracker at a 500Hz sampling rate. The experiment was controlled by PsychoPy (Peirce, 2007) using Python.

Stimuli. A black fixation cross was present throughout trials (0.48° visual angle) against a white background. Memory arrays (as seen in Figure 1) consisted of four differently colored squares (1.43° × 1.43°) presented equidistantly 2.86° from fixation. The different colors for the squares were selected at random from a pool of eight equiluminant (~58 cd/m^2) colors (in RGB space: red: [255, 128, 128], orange: [255, 134, 0], gold: [179,160,0], green: [0, 185, 0], teal: [0, 172, 172], blue: [153, 160, 255], purple [230, 128, 230], gray [166, 166, 166]). If the trial was a change trial, the replacement color was randomly chosen from the set of four unused colors to create the test display. During the maintenance phase as SO could be presented at an eccentricity of 7.63° to the left or right of fixation. The SO was either a black circle (.67° diameter) or a black arrow (1.43° × 0.67°).

Design. The experiment consisted of a 2 (Gaze: Saccade vs. Fixation) × 3 (SO: Feature vs. Spatial vs. Absent) repeated-measures design with the focal dependent variable of memory accuracy. Gaze conditions were blocked as were feature and spatial conditions leading to a total of four blocks, with SO absent trials intermixed throughout. SO absent trials appearing in the fixation and saccade blocks were considered as separate conditions, for ease of data analysis and to cater for potentially different preparation tactics in the gaze blocks (i.e., preparing to make an eye-movement in the saccade block). Participants were randomly assigned to one of four possible block orders that counterbalanced the order of gaze condition and SO type. Each experimental block consisted of 96 trials, with 32 of these being SO absent trials, leading to a total of 384 trials. Practice blocks of 12 trials occurred before the first two experimental blocks (one for each SO condition) and were not analyzed.

Procedure. The trial timing parameters were the same for each condition. Participants were required to hold fixation on the central fixation cross for 1,000 ms to start each trial, which began with the presentation of the memory display containing the four colored squares. The memory display was presented for 500 ms. After a 2,200 ms retention period the test display containing either the same four squares or a display with one differently colored square reappeared (50% of trials) and stayed on the screen until participants made a "same" (left arrow key) versus "different" (right arrow key) judgment.

The SO was presented 500 ms after the start of the retention period, for 1,200 ms, followed by a fixation display which was presented for 500 ms. Participants were required make a response within the 1,200 ms that the SO was presented, or the trial would cancel and display the message "Too Slow." This was done to ensure that the retention period for the memory test was the exact same length for both SO present and absent trials.

In the fixation block and on SO absent trials participants were required to maintain gaze on the central fixation cross throughout the trial. If the gaze moved out of the fixation area (3.53° × 3.53°) a message reading "Don't look away" appeared and the trial would be cancelled (to ensure that the covert attention condition was not contaminated by saccades to the SO). For the saccade block participants were required to make a saccade to the onset of the SO. If their gaze were not on the SO area (3.53° × 3.53°) the key responses would not be registered. This ensured that participants first attended the SO overtly and then made the response.

The possible SOs differed across conditions. In the feature condition a left or right pointing arrow was presented on a random side of fixation. Participants responded with the 'a' key for a left arrow and the 'd' key for the right arrow. This condition required the participants to attend the features of the object. In the spatial condition a circle was presented on the left or right of fixation and participants responded to the location of the SO (left, right) with the 'a' and 'd' keys, respectively. On SO absent trials participants did not make a response and were instructed to maintain fixation throughout the retention period in both overt and covert attention conditions.

Results

Accuracy for the SO task was high, and trials with incorrect responses to the SO were excluded (1.74% of trials). As shown in Figure 2, the presence of an SO reduced memory accuracy, indicating that the secondary task interfered with VWM performance. A 2 (Gaze Block: Fixation vs. Saccade) × 3 (SO task: Feature vs. Spatial vs. Absent) repeated-measures analysis of variance (ANOVA) was conducted on memory accuracy. Contrary to the transsaccadic prediction, no effect of Gaze was present $F(1, 24) = 0.208$, $p = .653$, $\eta_p^2 = .009$. There was a main effect of SO task, $F(2, 24) =$

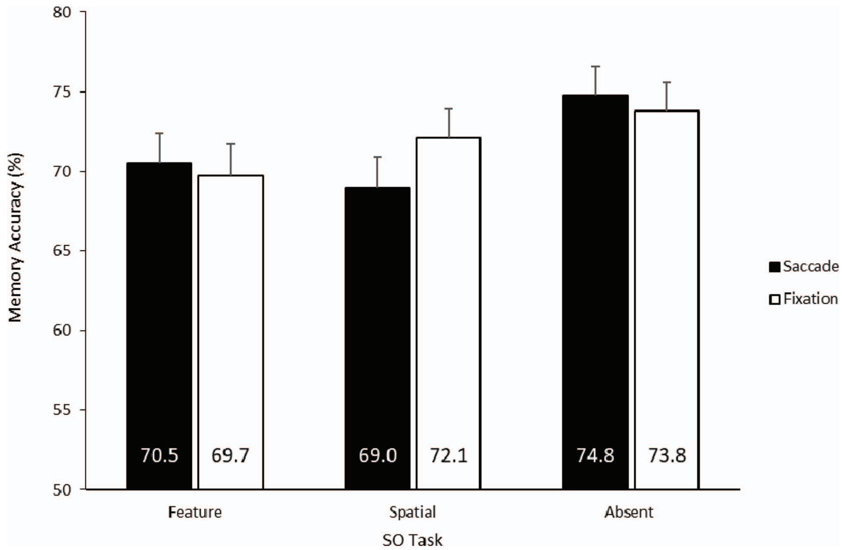

Figure 2. Mean accuracies for the change-detection task as a function of gaze condition and secondary-object (SO) type in Experiment 1. Error bars represent within-subjects 95% confidence intervals according to Loftus and Masson (1994).

4.54, p = .002, η_p^2 = .223, with higher accuracy for the SO Absent condition compared with both the Feature, $t(24)$ = 3.46, p = .002, 95% confidence interval (CI) [1.70, 6.74] and the Spatial, $t(24)$ = 2.95, p = .007, 95% CI [1.13, 6.38] attention conditions. Feature and Spatial conditions were not significantly different from each other, $t(24)$ = 0.37, p = .713, 95% CI [−3.03, 2.10]. There was, however, a trending interaction between Gaze and SO task $F(2, 24)$ = 2.78, p = .072, η_p^2 = .104.

For the Feature SO task there was interference in comparison with SO Absent trials in both the Saccade block, $t(24)$ = 2.74, p = .011, d = 0.55, 95% CI [1.09, 7.71], and as predicted by the unified view; the Fixation condition, $t(24)$ = 2.55, p = .018, d = 0.51, 95% CI [0.77, 7.31]. These conditions did not differ from each other, $t(24)$ = 0.50, p = .622, d = 0.10, 95% CI [−2.37, 3.78]. A paired t test comparing the Fixation and Saccade blocks for the Spatial SO task revealed decrements in accuracy for the Saccade compared with the Fixation block, $t(24)$ = 2.45, p = .022, d = 0.49, 95% CI [0.50, 5.80]. When compared with SO-absent trials, only the accuracy in the Saccade trials were impaired, $t(24)$ = 3.78, p = .001, d = 0.76, 95% CI [2.67, 9.12], whereas the Fixation condition showed no interference by the SO, $t(24)$ = 1.01, p = .325, d = 0.20, 95% CI [−2.67, 4.95].

Discussion

Experiment 1 investigated the effects of gaze and concurrent attentional tasks upon a VWM task. The key variable that influenced memory accuracy was attention directed toward the features of the SO. In the FBA condition, the presence of an SO reliably impaired memory performance. Critically this was independent of gaze condition with the effect occurring in both the covert and overt conditions, suggesting that the interference is because of the FBA deployed to the SO. This is in line with Kiyonaga and Egner's (2013) proposal that attending an item utilizes the same mechanisms as retaining it in working memory.

In the spatial SO condition making an eye movement to the SO did impair memory performance compared with the covert attention condition. This impairment is likely because of the obligatory coupling of attention and eye-movements (e.g., Deubel & Schneider, 1996). Conversely, in the fixation (covert attention) condition only the relevant spatial information for the SO was processed, producing no competition with VWM contents. Studies have shown that even when cognitive resources are not fully strained irrelevant items (or features) are not always processed or attended (Eitam, Yeshurun, & Hassan, 2013; Persuh, Gomez, Bauer, & Melara, 2014). The underlying factor between the three conditions that invoked interference was the FBA directed toward the SO, arguing against the separation of FBA and VWM.

This conclusion is, however, to some extent hampered by observed trending interaction. This leaves open the possibility that there was no reliable difference between the overt and covert spatial SO conditions (but rather interference in all four SO conditions). In this case, the observed effects would likely be because of generalized dual-task costs. In the SO-absent condition no responses were required, compared with the requirement to make a judgment in each of the four SO conditions. It is possible that the interference effect was merely because of response or decision related factors impacting VWM.

A second potential concern is that participants were always required to shift spatial attention when the SO was present, but not when the SO was absent. This could have posed a problem especially in the feature trials where responses were to the shape of an arrow. Arrows can automatically direct spatial attention elsewhere, because of their symbolic meaning (Hommel, Pratt, Colzato, & Godijn, 2001). Hence, it is possible that the instruction to attend to the shape of the arrows created interference in attentional processes when coupled with the spatial shift. This possibility would also argue against the interpretation that it was specifically the allocation of FBA to the SO that interfered with VWM contents.

Experiment 2

The aim of Experiment 2 was to distinguish effects of FBA versus shifting spatial attention on VWM, as well as assessing possible effects of later, response-related processes on VWM. To that aim, Experiment 2 examined the effects of FBA versus saccades on VWM performance when (a) the SO was a ring with a gap in it (Landolt C), (b) the requirement to shift attention was varied, by presenting the SO centrally as well as peripherally, and (c) responses were enforced in the absence of the SO in one conditions compared with a no-response condition to assess possible effects of later decision or response-related processes on VWM.

Experiment 2 included two blocked conditions. First a block where participants were instructed that the SOs were irrelevant; labeled the "Ignore" block. Second, a block where participants were required to respond to the SO; labeled the "Attend" block. Within both blocks, a centrally presented SO was intermixed, allowing participants to attend to the object without needing to shift gaze or spatial attention. This was compared with a peripheral SO, requiring a saccade to its location in both the Ignore and Attend blocks. The task in the Attend block was to respond to the direction of the Landolt C ensuring FBA. SO absent trials were intermixed throughout the experiment and, importantly, in the Attend condition participants were required to make a response if the SO was absent. Comparing VWM performance in the SO absent condition across Ignore and Attend blocks allows assessing decision and response-related effects upon VWM. Moreover, comparing performance between the central and peripheral conditions allows distinguishing effects of spatially shifting attention and attending to the SO features.

If attending the SO's features causes VWM interference then accuracy decreases would be expected in the Attend block for the central SO, and in both conditions for the peripheral SO. This holds because making an eye movement to the peripheral SO should guarantee that FBA is deployed, leading to VWM interference. Conversely if items only interfere with VWM when making a saccade (e.g., Tas et al., 2016), then memory interference is predicted only when the SO is presented peripherally (requiring a saccade), regardless of the response requirements. Moreover, the SO absent control condition should not differ between Attend and Ignore blocks, showing that VWM interference cannot be explained by response requirements or generalized dual task costs.

Method

Participants. Twenty-four (17 female) undergraduate students from the University of Queensland participated in this study for course credit and were included in data analysis (out of the 27 recruited). Mean age was 20.5 years ($SD = 3.13$) and all reported normal or corrected-to-normal vision. One participant was excluded from all analyses because of scoring at chance levels in all condition and two were excluded for incorrectly responding to the SO.

Stimuli. Stimuli and apparatus was identical to that used in experiment one except for the SOs. In all Conditions Landolt Cs were used, which had a diameter of 0.48° and a gap of 0.01°.

Design. The experiment consisted of a 2 (Task: Attend vs. Ignore) × 3 (SO: Central vs. Peripheral vs. Absent) repeated-measures design, with the main DV of interest being memory accuracy. The Attend and Ignore conditions were presented in separate blocks, with the three SO conditions intermixed within blocks. The order of blocks could not be successfully counterbalanced across participants, because there is a high probability that after completing an Attend block participants would still automatically categorize (i.e., attend) to the SO's stimulus features in a following Ignore block. To prevent possible contamination of responses by preceding Attend blocks, all participants completed the Ignore block before the Attend block. There were 56 trials for each combination of response and SO conditions, leading to a total of 336 experimental trials. Before commencing each block 12 practice trials were completed, which were not analyzed.

Procedure. Because of the Ignore condition, participants were instructed to move their gaze if the Landolt C was presented peripherally, and otherwise to maintain fixation. Moreover, participants were instructed that the Landolt C ('C') was irrelevant and required no keyboard responses. In the Attend condition participants were told that they now had to make an additional response to the 'C.' Responses were required based on the direction the Landolt C was facing, regardless of where it appeared on the screen. Specifically, participants were instructed to press the left and right arrow keys when the C was facing left or right, and down arrow key when the SO was absent. Trial timings were the same as Experiment 1.

Results

Excluding incorrectly responded SO trials and wrongly directed gaze trials led 3.2% of trials being excluded. A 2 (Task: Attend vs. Ignore) × 3 (SO: Peripheral vs. Central vs. Absent) repeated measures ANOVA on mean memory accuracy revealed a main effect of Task, $F(1, 23) = 16.36$, $p = .001$, $\eta_p^2 = .416$, such that Attend accuracy was lower compared with Ignore. The main effect of SO was marginally significant, $F(2, 23) = 3.65$, $p = .058$, $\eta_p^2 = .127$ and, importantly, these effects were qualified by the predicted Task × SO interaction, $F(2, 23) = 6.60$, $p = .003$, $\eta_p^2 = 223$.

The simple effects of SO showed a significant decrease in accuracy in the Attend condition compared with the Ignore conditions, both for Peripheral: $t(23) = 5.60$, $p < .001$, $d = 1.14$, 95% CI [6.74, 14.65], and Central SOs: $t(23) = 2.43$, $p = .023$, $d = 0.50$, 95% CI [0.69, 8.51], in line with the predictions made by the FBA hypothesis (see Figure 3). The difference between Attend and Ignore was not present for SO absent trials, $t(23) = 0.19$, $p = .859$, $d = 0.04$, 95% CI [−4.54, 5.47], showing that the reduction in memory accuracy in the Attend condition was not because of the response requirements or dual task demands.

A 2 × 2 ANOVA comparing the peripheral versus central SO across Attend and Ignore conditions revealed a marginally significant interaction, $F(1, 23) = 4.36$, $p = .048$, $\eta_p^2 = .159$, reflecting that the difference between Attend and Ignore blocks was larger for the Peripheral SO than the Central SO.

Discussion

The results from Experiment 2 are in line with the predictions of the unified theory of FBA and VWM; that attending to an item's

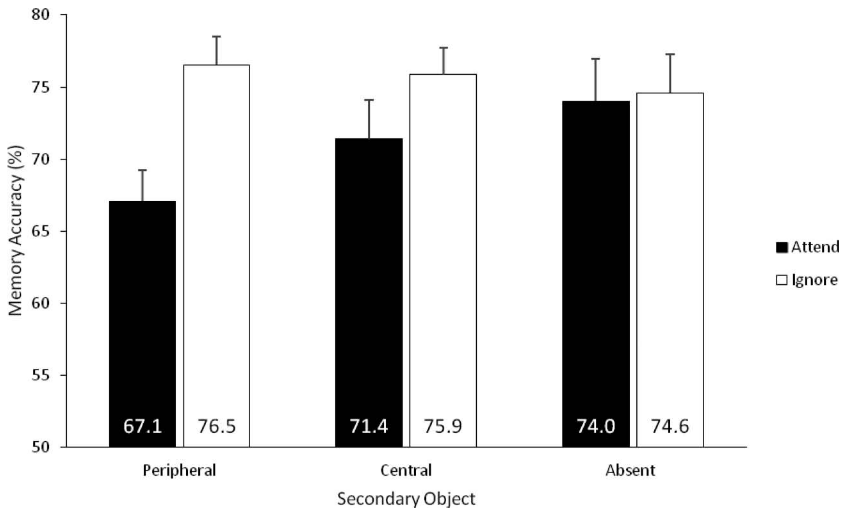

Figure 3. Mean memory accuracy as a function of task condition and secondary-object type in Experiment 2. Error bars represent within-subjects 95% confidence intervals.

features will lead to interference in VWM. When FBA to the SO was enforced the interference effect was present regardless of whether attention was shifted overtly to the peripheral SO or when attention remained at central fixation. More important, this effect was only found in the Attend condition, which required processing of SO features. Conversely, when the features of the SO were task irrelevant, in the Ignore condition, there were no memory impairments. It was confirmed that this difference was not because of added cognitive load as there was no accuracy cost for responding to the absence of the SO. Moreover, it is unlikely that the effects were because of the fixed order of blocks (Ignore completed before Attend), as memory performance in the SO Absent control conditions were the same. Together these findings suggest that the interference from a secondary item only occurs when its features are attended. A surprising finding was that a saccade to the irrelevant SO did not initiate VWM interference.

The peripheral condition in the Ignore block was almost a direct replication of the corresponding condition of Tas et al. (2016), where the authors found that making a saccade to an irrelevant SO caused memory interference. A potential explanation is that participants in Tas et al. (2016) did not view the SO as entirely task-irrelevant or unimportant. In the current study participants were informed that the SO was completely irrelevant and instructed to ignore it. It is possible that this allowed participants to prioritize the VWM contents, such that they were shielded from interference. Previous studies have shown that top-down controlled processes can shield VWM contents from interference by salient items that are known to be irrelevant (Gaspelin, Leonard, & Luck, 2015; Sawaki & Luck, 2010 see also Desimone & Duncan, 1995) The shielding of VWM contents was not possible when responses were required to the feature of the SO, which rendered the SO task-relevant. The contrast between the conditions suggests that a saccade is not a sufficient condition for VWM interference. However, an unpredicted result was that a greater magnitude of interference was observed in the peripheral SO condition compared with fixation condition in the Attend block, this suggests that there is some form of interaction between the saccade and the attention directed toward the SO (see General Discussion).

Experiment 3

In the previous experiments we have demonstrated interference from an attended SO upon a full capacity VWM load. The claims of Kiyonaga and Egner (2013) suggest interference should only occur when attention or memory is at capacity as there would be insufficient amounts of the "shared resource" to complete both tasks. However, it is possible that FBA simply disrupts VWM contents without it necessarily sharing the same resource. If the previously seen effects were caused by other (unspecific) aspects of the FBA task, then interference should still be observed when memory load is not at capacity. If, however, the interference effect is because of the shared resource reaching capacity limitations then there should be no interference when attention and memory task jointly do not reach full capacity. Experiment 3 distinguished between these possibilities by varying varied memory load; adjusting the number of items in the to-be remembered array from two-items (low load) to four-items (full load).

Method

Participants. Twenty-six volunteer participants (14 female) from the University of Queensland participated for reimbursement of $20 and were included in data analysis. Mean age was 22.3 years (*SD* = 2.69). Twenty-nine participants were originally tested, 2 were excluded for chance performance in the memory task, and 1 for incorrectly responding to the SO.

Design and procedure. Stimuli were presented on 17-in. CRT monitor. Memory and SO stimuli were the same as used in Experiment 1 and 2. The experiment used a 2 (SO: Absent vs. Present) × 3 (Memory Set Size: Two vs. Three vs. Four) repeated measures on the focal DV of memory accuracy. Participants completed 10 practice trials before commencing. Memory set size was blocked with SO absent and present trials intermixed within. Each set-size block consisted of 64 trials and was repeated a second time, leading to a total of 384 trials. Block order was counter balanced. On 50% of trials a peripheral Landolt C was presented, to which participants responded to its direction. The other 50% were SO-absent trials to which participants did not have to make a response. Gaze was no longer monitored and participants were given no instructions regarding their eye-movements.

Results

Trials with incorrect responses to the SO were excluded (5.4% of trials). A 2 (SO: Absent vs. Present) × 3 (Memory Load: Two vs. Three vs. Four) repeated-measures ANOVA was conducted on VWM accuracy (see Figure 4). A main effect of SO, $F(1, 25) = 25.41$, $p < .001$, $\eta_p^2 = .504$, was present, such that the presence of SOs led to lower accuracy. The memory set size effect was also significant, $F(2, 25) = 160.20$, $p < .001$, $\eta_p^2 = .865$, with higher accuracy for Two items compared with Three, $t(25) = 10.73$, $p < .001$, 95% CI [5.91, 8.71] and Four, $t(25) = 15.81$, $p < .001$, 95% CI [14.55, 18.91]. The Three load condition also performed better than the Four load condition ($t(25) = 9.19$, $p < .001$, 95% CI [7.31, 11.54]). These results were qualified by a SO × Set size interaction $F(2, 25) = 3.76$, $p = .030$, $\eta_p^2 = .131$.

The simple effects of Memory Load showed a significant decrease in accuracy in the SO Present condition compared with the Absent condition only in the Four-load condition, $t(25) = 4.65$, $p < .001$, $d = 0.91$, 95% CI [3.32, 8.61]. This difference was not seen for the Three load: $t(25) = 1.55$, $p = .133$, $d = 0.30$, 95% CI [−5.08, 0.71], or the Two load set, $t(25) = 1.67$, $p = .108$, $d = 0.33$, 95% CI [−3.17, 0.33].

Discussion

Results from Experiment 3 demonstrated SO interference only while memory load was at full capacity. When load was not at capacity the effect of attending to the SO was diminished and proved unreliable. This suggests that the competitive interaction between FBA and VWM will only be observed when cognitive VWM resources are sufficiently strained. This challenges the notion that FBA having a generalized interference effect on VWM can account for the results seen in Experiment 1 and 2, and instead supports the idea that VWM and FBA are competing for a capacity limited shared resource.

Experiment 4

The previous experiments demonstrated that FBA can interfere with feature-based VWM, indicating that the findings of Tas et al. (2016) were due the separation between spatial attention and FBA, not a separation between attention and VWM. However, the previous experiments did not provide direct, unequivocal evidence for the domain-specificity of VWM, namely the separation between spatial and feature-based VWM. The goal of Experiment 4 was address this question, by testing whether spatial information, but not feature-based information, interferes with spatial working memory (SWM). This experiment followed a similar design to that of Experiment 1. Either a spatial (location judgment) or a feature (color judgment) SO was attended in the retention period of a spatial memory array with gaze controlled through saccade and fixation blocks. If the SWM interference effect follows the same domain restrictive interactions as seen in the previous experiments then attending a spatial SO should cause interference in both the saccade and fixation conditions. In turn, the feature SO should only produce interference in the saccade block (as it enforces a shift of spatial attention; Shepherd, Findlay, & Hockey, 1986), but not in a fixation condition that does not involve spatial shifts of attention or gaze. This condition should produce no interference as attending feature information has no competitive overlap with the SWM contents. A corresponding finding would support the view that attention and working memory systems share common resources, though only in a domain-specific manner, maintaining the separation between spatial and feature-based domains.

Method

Participants. Nineteen volunteer participants (12 female) from the University of Queensland participated for reimbursement of $20

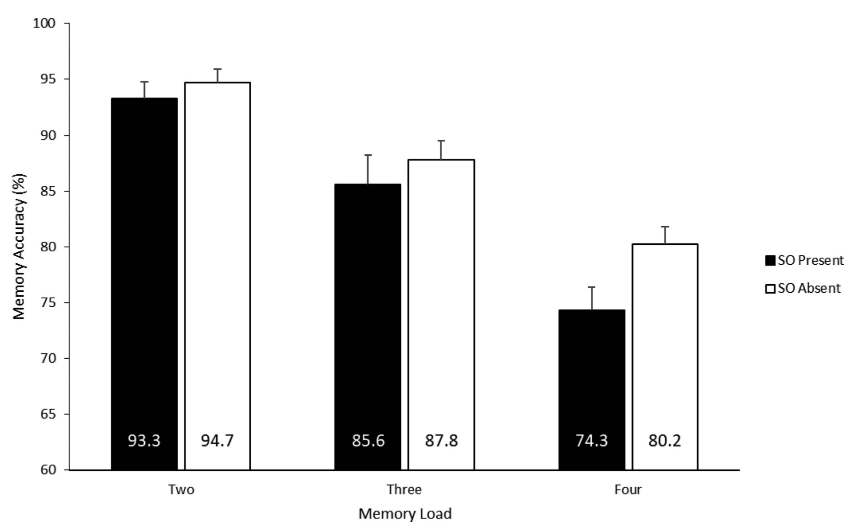

Figure 4. Mean memory accuracy as a function of memory load and secondary-object (SO) presence in Experiment 3. Error bars represent within-subjects 95% confidence intervals.

and were included in data analysis. Mean age was 22.1 years (SD = 2.23) and all reported normal or corrected-to-normal vision. Twenty-seven participants were originally tested, however, 8 were excluded, 3 for scoring at chance level, 2 for scoring at ceiling, and 3 for poor SO accuracy (<55% in either the feature or spatial task).

Stimuli. Memory arrays in Experiment 4 consisted of four black squares (0.62° × 0.62°) presented in eight varying positions, on the outline an imaginary circle with a radius of 4.77°, excluding the horizontal and vertical meridians. All stimuli were presented against a gray background. SOs were presented at an eccentricity of 7.63° to the left or right of fixation and 0.46° above or below the center of the screen. The SO was a filled circle (.67°diameter) colored either red [255, 0, 0] or blue [0, 0, 255].

Design and procedure. The design of Experiment 4 was identical to that of Experiment 1, including using the same trial numbers for each condition. The procedures were also identical, with the only differences being introduced in the SO and the memory task.

The SOs presented differed across conditions. In the FBA condition participants were instructed to respond to the color of the SO (left arrow key for blue, right for red). Color judgments were chosen for the SO task as it is a purely feature task. It could be argued that the Landolt C direction judgments from Experiments 2 and 3 could require some spatial processing. Because the goal of the FBA SO in the fixation condition was to isolate the effect of attending features on SWM this SO was presented at fixation to prevent shifts in spatial attention. In the spatial condition the circle was presented on the left or right of fixation and participants responded to whether the SO was above or below the midline of the screen with the left (below) and right (above) arrows keys. This task was changed from the previous left or right judgment of Experiment 1 in an attempt to match the task difficulty of the color judgment. On SO absent trials participants did not make a response and were instructed to maintain fixation. The memory task in Experiment 4 was now a spatial task. Four squares were presented and participants were required to memorize their locations. The test phase consisted of a single square outline appearing and participants had to judge whether this square was in one of the same positions as in the memory set (the 'a' key) or in a different position (the 'd' key).

Results

Accuracy for the SO tasks were reasonably high, and trials with incorrect responses to the SO were excluded (11.6% of trials). There was no difference in SO accuracy between the feature (M = 90.4%) and spatial tasks (M = 86.6%), p = .095. A 2 (Gaze Block: Fixation vs. Saccade) × 3 (SO task: Feature vs. Spatial vs. Absent) repeated-measures ANOVA was conducted upon SWM accuracy (see Figure 5). A main effect of Gaze, $F(1, 18) = 33.56$, $p < .001$, $\eta_p^2 = .651$, was present, such that Saccade blocks had lower accuracy than Fixation. The effect for SO task was also significant, $F[2, 18] = 20.53$, $p < .001$, $\eta_p^2 = .533$, with higher accuracy for the SO absent condition compared with both the Feature, $t(18) = 3.65$, $p = .002$, 95% CI [2.34, 8.68] and the Spatial, $t(18) = 7.34$, $p < .001$, 95% CI [7.51, 13.52] attention conditions. Accuracy in the Feature condition was also higher than the Spatial condition ($t(18) = 2.59$, $p = .019$, 95% CI [0.94, 9.08]). These results were qualified by the Gaze × SO Task interaction $F[2, 18] = 6.46$, $p = .004$, $\eta_p^2 = .264$.

The simple effects of Gaze task revealed significant differences between Spatial, Feature and SO-Absent conditions in both Saccade ($F[2, 18] = 18.24$, $p < .001$, $\eta_p^2 = .503$) and Fixation blocks ($F[2, 18] = 10.46$, $p < .001$, $\eta_p^2 = .367$). In the Saccade block, both the Feature, $t(18) = 5.38$, $p < .001$, $d = 1.24$, 95% CI [6.32, 14.41] and Spatial SO, $t(18) = 6.05$, $p < .001$, $d = 1.39$, 95% CI [8.40, 17.32] conditions performed significantly lower than the SO absent condition, but not differently from each other, $t(18) = 0.94$, $p = .360$, $d = 0.215$, 95% CI [−8.09, 3.09] in line with the expectation that the saccades would interference with SWM. Con-

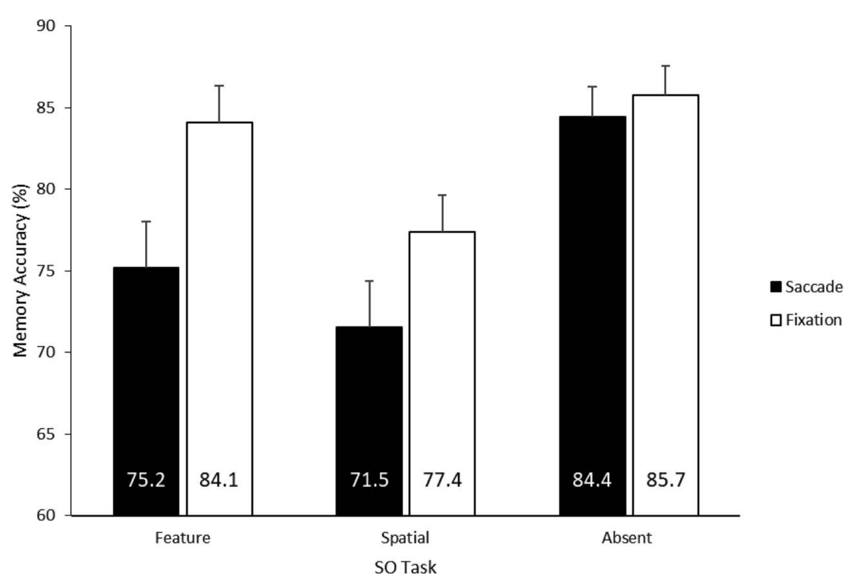

Figure 5. Mean accuracies for the change-detection task as a function of gaze condition and secondary-object (SO) type in Experiment 4. Error bars represent within-subjects 95% confidence intervals.

versely, in the Fixation block interference was only seen from the Spatial SO, which significantly differed from the Feature SO, $t(18) = 3.47$, $p = .003$, $d = 0.80$, 95% CI [2.96, 12.07] and Absent condition, $t(18) = 4.50$, $p < .001$, $d = 1.03$, 95% CI [4.36, 11.97]. The Feature and Absent conditions did not differ, $t(18) = 0.33$, $p = .744$, $d = 0.08$, 95% CI [−4.77, 3.47].

Conversely when examining the effects of SO tasks, differences were revealed with Saccade conditions performing lower than Fixation as predicted for the Feature SO: $t(18) = 5.29$, $p < .001$, $d = 1.21$, 95% CI [6.60, 15.30], but surprisingly also the Spatial SO: $t(18) = 3.25$, $p = .004$, $d = 0.75$, 95% CI [2.10, 9.77]. The SO-absent trials did not differ $t(18) = 0.72$, $p = .482$, $d = 0.16$, 95% CI [−4.84, 2.38].

Discussion

Experiment 4 demonstrated a pattern of results supporting the domain specificity between feature-based and spatial working memory. In all conditions that required spatial attention, interference was observed with SWM. Both an overt and a covert shift of spatial attention caused decrements in memory accuracy and this also occurred when a saccade was made in the feature SO condition. The only SO that did not produce interference was the feature SO presented at fixation; which required no spatial shifting or processing. These results highlight the specificity of SWM and VWM systems and the interactions with their respective form of attention. Interesting a similar interaction to the one observed in Experiment 2 was reoccurred. When making a saccade, the interference effect was enhanced for the spatial SO compared with when fixation was maintained (discussed further in General Discussion).

General Discussion

The current study aimed to untangle the influence of four factors upon VWM performance; overt versus covert attention and spatial versus feature-based attention. The key finding from the study was that it is the attention directed toward a target object's features that causes competition with feature-based VWM. Critically this interference was observed independently of eye-movements in Experiment 1, where the effect was seen for both an overt and a covert shift of attention. This was replicated in Experiment 2 when the observed effect was seen again for a centrally presented SO, one that required neither eye-movement nor shift of spatial attention. This challenged the conclusion of previous research which argued that VWM was the mechanism allowing for transsaccadic stability and, thus, saccades are the cause of VWM interference (Tas et al., 2016). The current study accounted for these results by highlighting the importance of the domain distinctions in attention and memory tasks. Attending to spatial information did not interfere with VWM (with an exception, discussed below) and, conversely, attending to feature information did not compete with SWM. A critique of the current study was that the SO conditions a judgment response was required to the SO compared with a no response SO-absent condition. Experiment 2 accounted for this issue by incorporating a judgment response to the SO-absent condition. This condition did not affect memory accuracy and from this we can infer that the interference seen in the SO conditions was not from response based interference. Together these results suggest that FBA was responsible for observed interference with the maintained VWM load.

There were, however, certain requirements that needed to be met for an attended SOs features to affect VWM. When attending to another object it was vital that this item was task relevant, as seen in Experiment 2. According to Desimone and Duncan (1995) stimuli compete for cognitive resource allocation and that this competition is driven by current top-down goals. When SOs were irrelevant in Experiment 2 no interference was observed, suggesting that the current goal of retaining VWM information "won" the competition for the limited resource. The second requirement for competition was that memory load needed to be high. In Kiyonaga and Egner's (2013) unified account of attention and working memory they stated that to observe the competitive interactions between attention and working memory one or both of these systems must be under sufficient cognitive strain. The results from Experiment 3 fall in line with these predictions; interference was not observed at memory loads of two or three, only at four. This rules out the alternate explanation that FBA simply disrupts all memory processes, and instead suggests a more complex relationship; one in which memory and attention rely upon a shared resource. At high memory load there were insufficient resources to attend to the SO; thus, some of the resources dedicated to maintenance needed to be "sacrificed" to complete the secondary task. At lower memory loads no sacrifice was necessary as memory was not running at capacity.

The described pattern of results seems to neatly fit into the prediction of a unified but domain-specific for FBA and VWM; however, two conditions within the study present seemingly contradictory results. The saccade to spatial-SO condition in Experiment 1 led to VWM interference and originally this was attributed to FBA being automatically directed to the saccade target object. Experiment 2, however, seemed to contradict this conclusion. When participants made a saccade to an irrelevant SO no interference was observed. The key difference between these conditions was the *task-relevance* of the stimulus. In Experiment 1 the SO was task-relevant in accordance with top-down goals, and when paired with the attention facilitating saccade (Shepherd et al., 1986) it is possible that performing the judgment task led to both relevant (spatial) and irrelevant (feature) information of the SO being attended. In Experiment 2 the SO was completely irrelevant and top-down goals were focused on maintaining the memory load. It is possible that despite the saccade the memory contents could be shielded from SO interference, or prioritized over the SO. Eymond, Cavanagh, and Collins (2016) found a lack of feature priming from a saccade target upon a subsequent visual search. Participants first saccaded to an irrelevant stimulus which was either congruent, incongruent, or neutrally colored with regard to a subsequent pop-out search task. Their results revealed no priming effect on the search. The authors claimed that the irrelevant item was not attended or automatically encoded into VWM. This and the presented results suggest that there is not an obligatory relationship between FBA and saccades.

Experiments 1 through 3 demonstrated the impact of FBA on VWM under the assumption that spatial and feature-based systems are strictly separate. Sensorimotor theories of working memory state that working memory is a property that emerges from specific sensory systems (D'Esposito & Postle, 2015) and previous research has drawn distinctions between different forms of working memory (Courtney et al., 1996) and different forms of attention (de Haan & Cowey, 2011). Experiment 4 helped to reinforce the assumption of the previous experiments by flipping the design of Experiment 1 and showing the effect of spatial attention on SWM. Both a saccade (highly linked to spatial attention; Shepherd et al., 1986) and attending to spatial information independently impaired memory accuracy, whereas FBA on its own did not produce interference. This also rules out the explanation that FBA simply has a disruptive effect on all domains of working memory. These results again highlight the link between feature-based and spatial attention and their respective forms of working memory.

The discussed results uniformly showed that saccades are not necessary for interference to occur with VWM or SWM. However, in Experiments 2 and 4, saccades had an additive effect when combined with an SO task. Both the peripheral condition in Experiment 2 and the spatial saccade condition in Experiment 4 produced more interference when compared with the respective fixation conditions. A saccadic target receives processing at a higher acuity than a peripheral stimulus (Provis, Dubis, Maddess, & Carroll, 2013), and it has been shown that there is more neural activation for an overtly compared with covertly attended stimulus (Beauchamp, Petit, Ellmore, Ingeholm, & Haxby, 2001; de Haan, Morgan, & Rorden, 2008). It is possible that as saccades are so often linked with goal-directed behavior (i.e., in most circumstances the currently fixated item is task-relevant and vice versa), an item that receives an overt shift of attention is viewed as more important to top-down goals (Hayhoe & Ballard, 2005). This could explain the additional interference observed in the saccade conditions of Experiment 2 and 4. The prioritized SO is viewed as more important and resource consumption is biased toward it (i.e., Desimone & Duncan, 1995), leaving less spare resources for memory contents.

To conclude, the feature information of a secondary stimulus reliably interferes with VWM performance regardless of eye-movements, or shifts in spatial attention. There were two requirements for this interference to be observed, (a) that the SO was task-relevant and (b), that VWM load was high. These results support a modal specific shared resource view of attention and working memory (Kiyonaga & Egner, 2013; Postle, 2006). The systems are governed by a competition for this shared resource that is guided by the top-down goals (Desimone & Duncan, 1995) of the individual.

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