Unconscious Information Processing in Working Memory

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Abstract

The conventional understanding of working memory (WM) holds that memory contents are tied closely with conscious awareness. However, recent work in unconscious visual perception suggests that unconsciously perceived items may also be stored in WM. The purpose of this study was to extend these findings by establishing whether unconscious items held in WM also demand WM capacity. It was hypothesized that participants would be less accurate at a change detection task when more unconscious memory items were present. Twenty-eight undergraduate students participated. Participants looked through a mirrored stereoscope, which isolates visual input between each eye. A continuous flash suppression (CFS) paradigm was used to render items overlapping with a high contrast Mondrian-like pattern unconscious. During CFS, the visible memory array (3 items) was presented shortly before an invisible memory array (0, 1, or 2 items). After a retention interval, participants were asked to specify whether a test probe was of changed orientation and how confident they were of their answer. Finally, participants indicated whether or not they consciously observed any to-be-suppressed items using the Perceptual Awareness Scale. Fourteen participants remained after applying exclusion criteria based on task accuracy and perception of suppressed items. Analysis of the full 18 blocks revealed a null effect; however, analysis of the initial 6 blocks demonstrated a main effect of the number of invisible items on task accuracy $F(2, 28) = 4.26$, $p = 0.02$. This suggests that unconscious information may interfere with processing and storage of conscious information.

Unconscious Information Processing in Working Memory

Working memory is a dedicated system in the brain for storage and maintenance of short term information–a system thought to underlie many human thought processes (Baddeley, 2003). The theory of working memory assumes a limited attentional capacity supported by broader peripheral support systems. Visual working memory (VWM), a subsystem storing visual information, is thought to have a storage capacity of four objects (Zhang & Luck, 2008). Though traditional theories of working memory hold that the contents of working memory are closely tied to consciousness (Baars & Franklin, 2003; Baddeley, 2003), recent work has explored unconscious visual processes and their representations in working memory (Bergström & Erikkson, 2015; Pan, Cheng, & Luo, 2012**;** Pan, Lin, & Soto, 2014; Soto, Mäntylä, & Silvanto, 2011; Underwood, 2018).

If unconscious visual information can be represented in working memory, VWM should accurately encode, store, and retrieve unconscious information (Soto & Silvanto, 2014). Similarly, unconscious information in VWM should also occupy storage capacity. In line with this prediction, studies have found evidence suggesting that unconscious information may be durably represented in working memory (Bergström & Erikkson, 2015; Soto, Mäntylä, & Silvanto, 2011), while others have found that unconscious information can displace visible items being held in VWM (Underwood, 2018). This study aimed to replicate the findings of Underwood (2018) by employing a change detection paradigm to examine the impacts of unconscious information on VWM capacity. This work also intended to examine the influence of perceptual grouping cues as a moderator of unconscious information processing in VWM.

Work employing a change detection paradigm has found that items suppressed from conscious perception can be durably represented in visual working memory. In an initial experiment, Soto and colleges (2011) presented subjects with a masked memory item (16.67 ms, Gabor patch, a type of grating) followed by a delay period and a subsequent memory test in which participants rated whether the Gabor patch rotated clockwise or counterclockwise. In each trial, participants' subjective perceptual experience of the masked memory item was measured using the four-point perceptual awareness scale (PAS; *1= did not see anything; 2= maybe saw something; 3= saw the stimulus but not its orientation; 4 = saw the stimulus and its orientation*). Results indicated that participants were able to discriminate orientation changes at above chance levels (approximately 56% accuracy), even when they were completely unaware of the memory item (PAS=1).

In follow-up experiments, Soto and colleagues (2011) investigated whether distractor Gabor cues would interfere with maintenance of the unconscious Gabor cues. A second experiment introduced a visible distractor Gabor cue, while a third experiment introduced brief and masked intervening distractors (16.67 ms duration followed by a mask). In both experiments, distractor cues were presented during the retention interval and consisted of congruent or incongruent orientations. Findings from these experiments showed that masked distractors interfere with maintenance of memory items more so than visible distractors. Moreover, even in the presence of distractor cues, tilt discrimination remained at above chance levels (approximately 58%). Taken together, these experiments suggest that visual working memory can encode, maintain, and access unconsciously perceived information.

A study conducted by Bergström and Erikkson (2015) extended these findings by using continuous flash suppression (CFS) to investigate whether unconsciously perceived information could be retained in working memory over a varying retention interval. CFS is a common method used in studies evaluating the processing of unconsciously perceived information in working memory (Carmel, Arcaro, Kastner, & Hasson, 2010; Tsuchiya & Koch, 2005). CFS relies on the creation of binocular rivalry, or the perceptual phenomenon in which each eye is presented with an artificial, subtly different image at corresponding retinal locations. Rather than seamlessly fusing the two images as usual, binocular rivalry causes the visual system to oscillate conscious perception between each eye, forcing one image into dominance while suppressing the other (Blake, 2001). Binocular rivalry requires isolating the visual input between each eye using a mirrored stereoscope, color goggles, or prism goggles. CFS is a strong form of binocular rivalry which presents a low-contrast, static image to one eye and a high-contrast, rapidly changing image to the opposite eye (e.g. a Mondrian-like pattern flashing at 10-20 Hz). The visual salience of the high-contrast image forces rivalry to be dominated by the eye that receives it, rendering the low-contrast image suppressed from conscious awareness (Kouider & Dehaene, 2007).

In the study conducted by Bergström and Erikkson (2015), participants looked through a mirrored stereoscope and were instructed to retain the spatial location of a memory item (a face) for five or fifteen seconds. In one condition, both eyes were presented with the memory item (conscious condition), while in another, one eye was presented with the memory item and the other with a dynamically flashing Mondrian (non-conscious condition). In a control condition, no memory item was presented to one eye, while the other was presented with the dynamically flashing Mondrian. After a retention interval, a face probe was presented and subjects were asked to evaluate whether the probe changed location. Similar to experiments by Soto and colleagues (2011), participants completed a PAS rating after each trial to indicate how aware they were of the memory item (*1= no perceptual experience; 2= vague perceptual experience; 3= clear* *perceptual experience*). Results showed that participants performed at above-chance levels in detecting changes in invisible and visible items. What's more, PAS scores given in the non-conscious condition indicated that CFS sufficiently suppressed visual stimuli sent to the non-dominant eye from conscious.

The work discussed above suggests that unconscious information can be robustly encoded, maintained, and retrieved in visual working memory. If this is the case, then unconscious memory items should also demand working memory capacity (Dutta, Shah, Silvanto, & Soto, 2014). A recent series of experiments has examined this issue by investigating whether unconsciously perceived visual information occupies space in working memory (Underwood, 2018). From a discrete slots perspective of working memory (Cowan, 2011), working memory is composed of discrete slots, wherein individual chunks of memory information are stored temporarily (Rouder, Morey, Morey, & Cowan, 2011; Zhang & Luck, 2008). If unconscious information is stored in working memory, then unconscious items should compromise storage ability by a corresponding amount.

In the experiments conducted by Underwood (2018), subjects viewed memory items (Gabor patches; grayscale rectangular bars) through a stereoscopic display: some memory items were suppressed from conscious awareness using CFS, while others remained visible (all memory items presented simultaneously). Subjects then evaluated whether a probed memory item (visible or suppressed) was of a changed orientation after a retention interval. At the end of each trial, subjects were given the option to report *"Item Observed on Colored Side"* and the trial was disregarded if they reported seeing the item. Results indicated that accuracy detecting changes in visible items was significantly impaired as the number of suppressed items increased, revealing that unconscious memory items may alter working memory capacity. However, accuracy for detecting changed orientation of suppressed items was at chance levels. Therefore, it appears that they were not retained in VWM.

In a follow-up experiment, Underwood (2018) investigated whether the behavioral effect observed in Experiment 1 could be attributed to interruption of the maintenance process. Visible items were presented prior to suppressed items, allowing invisible items to be encoded independently without interruption. This asynchronous display of memory items was done to isolate the encoding and maintenance process in working memory. Contralateral delay activity (CDA) was also recorded during this experiment. CDA is an event-related potential (ERP) measured from the posterior lateral areas of the scalp, and is thought to be an index of the number of items held in working memory at a time (Ikkai, McCollough, & Vogel, 2010; Luria, Balaban, Awh, & Vogel, 2016; Vogel & Machizawa, 2004). Results replicated the behavioral findings of the initial experiment, indicating that unconscious memory items interrupt maintenance or retrieval of visible items, but do not interfere with encoding. A drop in CDA amplitude shortly after presentation of the suppressed items supported this interpretation. Again, however, chance-level accuracy for suppressed items indicated that they were not stored.

Work examining the processing of unconscious visual information has provided only inconsistent evidence that unconscious information can be durably represented in working memory (Bergström and Erikkson, 2015; Soto et al., 2011; Underwood, 2018). Even if the phenomenon is valid, the mechanism by which unconscious information is stored and occupies capacity in working memory remains unclear. For instance, the relationship between perceptual sensitivity to unconscious information and accuracy is conflicting–whereas Soto and colleagues report no interaction, recent work has indicated an effect (Bona et. al., 2013; Lau & Passingham; 2006; Soto et. al., 2011). By varying the total number of to-be-retained items (conscious and unconscious) such that the total number remains within the commonly-postulated limit of four, it may be possible to observe this interference effect with greater granularity (Cowan, 2000). The interference effect observed in Underwood (2018) could also be moderated by other factors in visual information processing such as Gestalt organization cues.

One mechanism which may influence the interference effect reported in Underwood (2018) is perceptual grouping of memory items, which has been shown to bolster performance in visual working memory tasks (Peterson et. al., 2015; Woodman et. al., 2003). One series of experiments by Woodman and collogues (2003) investigated whether bottom-up perceptual grouping cues bias the entry of items into visual working memory. They hypothesized that if Gestalt cues influence working memory storage, the cue should increase the likelihood that other members of the same group are also stored. One experiment investigated the proximity grouping principle proposed by Wertheimer (1950), which states that nearby objects are more likely to be grouped together than far away objects. Participants viewed four or six colored squares in arrays; an initial array of memory items was presented followed by a test array in which participants indicated whether the arrays were identical or differed in the color of one item. The array of four squares was presented equidistantly, while the other array of six squares was presented as vertically oriented clusters to bias the formation of perceptual groups based on proximity. Prior to each trial, a white dot flashed in one of four possible monitor locations, biasing allocation of attention to the cued location in the sample array. Subjects were encouraged to remember all items equally well, regardless of the grouping cue. Results revealed that accuracy in the grouped uncued corner (*M = 81%)* surpassed accuracy in the equidistant ungrouped uncued corner (*M = 69%),* indicating that proximity-based Gestalt cues improve recall ability. However, grouping had a more limited effect on arrays within the storage capacity of visual working memory. This suggests that grouping may be a coping mechanism employed when VWM is under high load.

If Gestalt features such as proximity act as a chunking mechanism for increasing VWM capacity under high-load conditions, then the behavioral results reported by Woodman and colleagues (2003) should be reflected in neural savings. One experiment used the CDA to index the working memory load as a function of perceptual Gestalt cues (Peterson et. al., 2015). In this experiment, CDA was recorded as participants completed a change detection task. Four conditions consisting of varied Gestalt cues (connectedness and proximity) were included. Behavioral results replicated previous work showing that Gestalt cues benefit VWM storage (Brady & Tenenbaum, 2013; Lin & Luck, 2009; Peterson & Berryhill, 2013; Woodman et. al, 2003). What's more, the behavioral improvements to VWM were paralleled in the neural data by a selective reduction in CDA amplitude during the storage of grouped arrays. This suggests that grouped items are integrated into a single representation in VWM.

The work by Woodman and colleagues (2003) indicates that grouping cues can improve recall accuracy in items of the same group, especially under high-load conditions. These grouping-related performance improvements are also reflected by neural correlates of VWM load (Peterson et. al., 2015). Though this effect has been established for visible VWM change-detection paradigms, it has not been explored in the context of unconscious VWM. This effect may explain the non-linear interference effect observed in Underwood (2018) during high-load conditions. Importantly, if Gestalt-related information were also found to augment accuracy in unconscious information tasks this may support the notion that unconscious information is being durably represented in memory.

The Present Study

The present study examined whether unconsciously perceived information occupies space in working memory using a change-detection task similar to the one conducted in Underwood (2018). Previous work suggests that unconscious information can be durably represented in working memory (Bergström and Erikkson, 2015; Soto et al., 2011), while a recent study by Underwood (2018) indicates compromised capacity when more unconscious information is presented. Moreover, previous work has found that perceptual grouping information plays an important role in biasing the storage and retention of conscious information in VWM (Peterson, Gözenman, Arciniega, & Berryhill, 2015; Woodman, Vecera, & Luck, 2003). It is not currently clear whether this phenomenon translates to unconscious information storage. This study aimed to replicate results suggesting compromised VWM capacity in the presence of unconscious information items (Underwood, 2018), while also examining whether other factors such as Gestalt grouping cues bias the storage of unconscious information in VWM.

According to the discrete slots model of memory (Cowan, 2000), if unconsciously perceived memory items do occupy space in working memory, then their presence should correspond with reduced change detection for visible items presented during the retention interval. Therefore, we hypothesized that accuracy detecting changes in visible probes would decrease as the number of invisible items presented increased. We also predicted greater accuracy when Gestalt cues were stronger–that is, trials consisting of spatially closer items with more similar orientation would correspond with higher accuracy on visible probes.

Methods

Subjects

Twenty-eight undergraduate students enrolled at the University of Missouri-Columbia participated in the experiment for Psychology 1000 course credit. All participants were naive to the objective of the experiment. Before beginning the study, participants were allowed to review and sign an informed consent in compliance with the University of Missouri Institutional Review Board. Participants were only selected if they were 18 or above, had no history of neurological or psychological disorders, and had normal or corrected-to-normal vision. Participants were aged between 18 and 27 years (M = 19.4, SD = 1.9), and 18 participants were female. Fourteen participants were excluded from the study due to factors discussed below.

Apparatus

Participants sat in a dimly lit, noise-attenuated room and viewed a mirrored stereoscope placed 30 cm in front of a 32 cm computer display, responding to stimuli using a standard keyboard and mouse. Stimuli were presented using MATLAB (Mathworks, Natick, MA) and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997).

Stimuli

A mirrored stereoscope was used to isolate visual input between the left and right eye, causing the subjects' perceptual experience to be a result of two independent displays (Figure 1). The left and right displays were divided into medial and lateral segments, with visible items being presented in the lateral segments and suppressed items being presented in medial ones. Two arrays of memory items (height: 1.5 cm width: 0.2 cm; 1.8°) were displayed on the computer screen for 500 ms each. One array of memory items (0, 2, or 4 items), shown in the medial segment of the display, was suppressed using continuous flash suppression (CFS). The suppressed items shown medially to one display shared the same retinal location as the dynamic noise pattern (Mondrian-like pattern; height: 11 cm, width: 7 cm; flashed at a rate of 15 Hz) shown in the medial segments of the opposing display, suppressing the items from conscious perception. The other memory array (6 items) was presented in the lateral segments of the display. Because these were not masked by the Mondrian-like pattern presented to the medial segments of the opposing display, these items remained consciously perceivable to participants.

Procedure

Each trial began with 100 ms of CFS presented to the medial segments of one display (Figure 1). Following CFS onset, a 200 ms arrow appeared in order to direct the subjects' attention to the left or right hemifield. Therefore, although memory items were presented to both hemifields, participants only attended to items in the designated hemifield in each trial (half of the items in the visible or invisible array). After a 100 ms delay, the visible items (6 total) were presented for 500 ms in the lateral unmasked segments of the display. Since the lateral segments of each hemifield did not overlap with the Mondrian-like pattern, these stimuli remained conscious. After another 100 ms delay, the invisible item array was presented. The invisible items (0, 2, or 4 total) were presented for 500 ms in the medial segments of the display opposite to CFS. Since the medial-presented items shared the same retinal location as CFS, these items were rendered unconscious. On a third of trials, no invisible items were presented. During display of conscious and unconscious items, the perceived left and right displays were roughly symmetrical (i.e. each hemifield had the same number of stimuli at any point in time); however, subjects only attended to the side prompted by the arrow. The CFS mask offset 100 ms after the suppressed items disappeared. After the CFS mask offset, there was a 600 ms retention interval in which subjects were required to remember the items. Finally, a test probe of a single memory item was presented at the same location as an invisible or visible item had been. Test probes were presented only on the hemifield the subject was directed to attend to. During testing, participants indicated: (1) whether the test item presented on the screen changed orientation, (2) their degree of confidence of this change, and (3) whether they were aware of any invisible memory items shown on top of the Mondrian-like pattern as measured by the perceptual awareness scale (PAS) score. See Figure 1 for a schematic of the experimental procedure.

Scales

Perceptual Awareness Scale.

The Perceptual Awareness Scale (PAS; Soto et al., 2011) is a standard scale used to assess the degree to which subjects perceive unconscious memory items. Subjects were prompted to complete the PAS after each trial. Participants were instructed to enter a PAS value of 1 if they did not see anything, 2 if they maybe saw something, 3 if they saw the stimulus but not its orientation, and 4 if they saw the stimulus and its orientation.

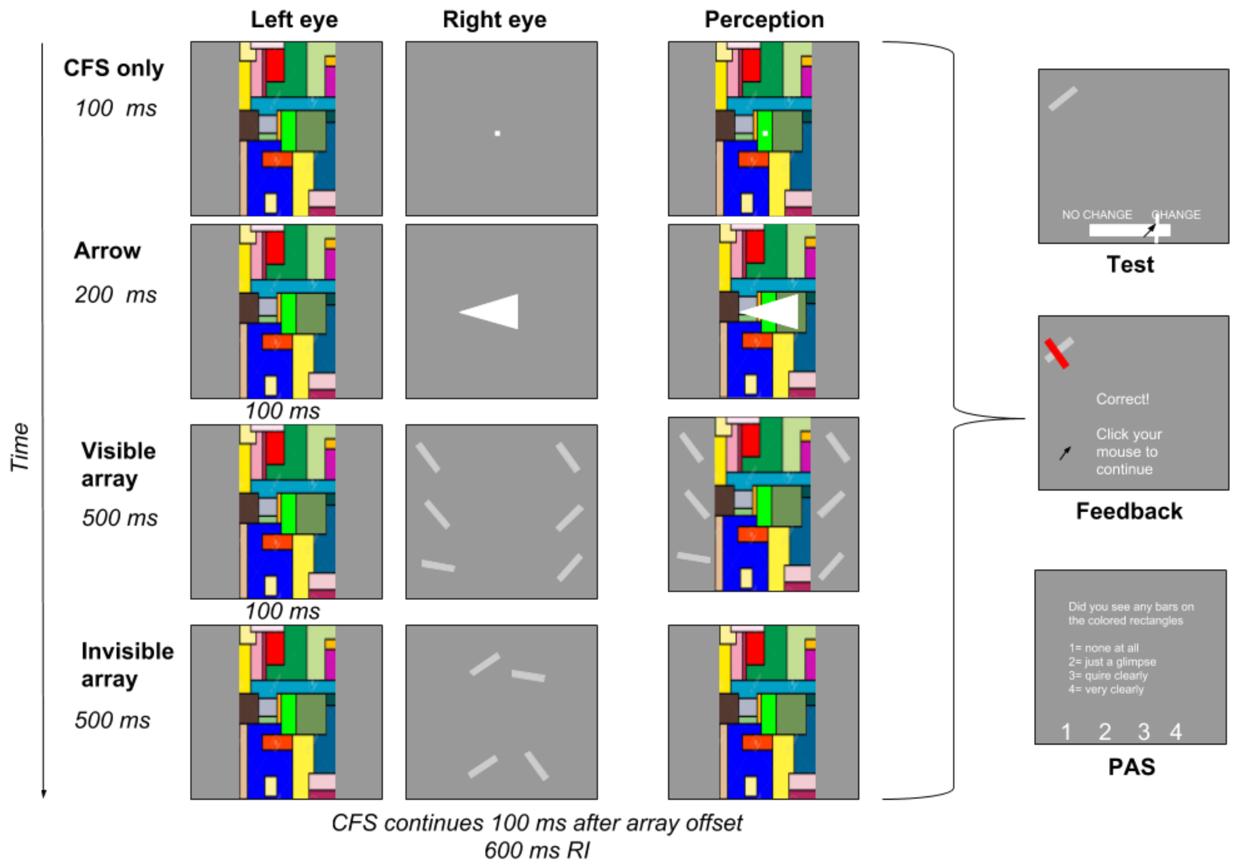

Figure 1. Schematic of the proposed experiment procedure. Top row, left panel: stimulus at the beginning of the trial. Second row, left panel: arrow directing subject attention appears. Third row, left panel: visible array is presented to participant. Bottom row, left panel: invisible array is presented to participant. Top row, right panel: test item is presented and subject specifies change/ no change, along with confidence. Center row, right panel: subject is presented with feedback. Bottom row, right panel: subject provides rating on perceptual awareness scale.

Data Analysis

Participants were excluded from analysis if they (1) scored less than 65% average accuracy on trials in which 3 visible and 0 suppressed items were presented, (2) scored greater than 65% accuracy on trials in which an invisible item was probed, or (3) reported (in a post-experimental questionnaire) that they saw suppressed items in over half of the trials. The first criterion was set in order to ensure that participants were allocating enough attention to the task, while the second two were established to guarantee that only data reflecting unconscious memory processing were included in analysis. Using these criteria, we included fourteen subjects in the final behavioral analysis. Fourteen subjects were eliminated from analysis: one due to fatigue while completing the task, thirteen due to low accuracy during the 3 visible 0 invisible item condition, and one due to reporting conscious sight of suppressed items over half of the time. Trials were excluded from analysis if subjects indicated they were aware of the suppressed item (PAS > 1), or their reaction time (RT) was too quick or slow to reflect engagement with the task (RT < .3 seconds or RT > 10 seconds). The first block was also excluded from analysis because it was used as a training period.

A one-way repeated measures ANOVA was used to compare the effects of the number of suppressed items on task accuracy between the three conditions (3/0, 3/1, 3/2, where the left side indicates the number of visible items in the trial and the right side indicates the number of suppressed items). Paired samples t-tests were used to evaluate the direction of observed effects for accuracy, confidence, and reaction time.

Results

One-way repeated measures ANOVA for the 3 invisible-items conditions indicated no main effect on task accuracy by the number of invisible items $F(2, 26) = 0.200$, $p = 0.81$. There was no difference in task accuracy when three visible items were presented with zero invisible items (3/0 condition; M = 79.2 % correct, SD = 0.40), compared with when three visible items were presented with one invisible item (3/1 condition; M = 78.5 % correct, SD = 0.41) [$t_{(13)}$ = -0.339, $p < .36$, one-tailed]. There was also no difference in accuracy when three visible items were presented with two invisible items (3/2 condition; M = 79.7 % correct, SD = 40.2), compared with the 3/0 baseline [$t_{(13)}$ = .303, $p < .61$, one-tailed]. Based on these results, we conducted an analysis of participant accuracy over time and observed that early blocks demonstrated a larger interference effect, with later blocks demonstrating a less-distinct difference between accuracies across the three conditions (see Figure 2). We reasoned that participants may have become fatigued during the experiment, and limited analysis to the first eight blocks. Therefore, blocks two through eight were included in the second analysis. Limiting analysis to these blocks of the experiment resulted in one additional participant included in analysis (previously excluded due to low accuracy in the 3/0 condition over all 18 blocks).

Once analysis was limited to these blocks, one-way repeated measures ANOVA for the 3 invisible-items conditions indicated a main effect on task accuracy by invisible items $F(2, 28)$ = 4.26, $p = 0.02$ (see Figure 3A). Reduced accuracy in detecting changes of probes was evident when three visible items were presented simultaneously with two invisible items (3/2 condition; M = 74.8 % correct, SD = 0.43) and when three visible items were presented with one invisible item (3/1 condition; M = 76.0 % correct, SD = 0.42), compared to when no invisible items were presented (3/0 condition; M = 81.7 % correct, SD = 0.38). The difference between the 3/0 condition and the 3/1 condition [$t_{(14)}$ = -2.57, $p < .01$, one-tailed], as well as the difference between the 3/0 and 3/2 condition [$t_{(14)}$ = -2.07, $p < .03$, one-tailed], demonstrated a statistically significant effect. There was no difference for visible probes in the 3/1 condition compared with the 3/2 condition. Change detection for suppressed items was near chance accuracy in both the 3/1 (M = 51.3 % correct, SD = 0.50) and 3/2 (M = 47 % correct, SD = 0.76) condition, supporting the assumption that the items were not consciously perceived.

Participants also responded more slowly when more suppressed items were present (see Figure 3B). We observed a significant difference in reaction time between the 3/0 (M= 2.51 seconds, SD = 0.29) and 3/1 (M = 2.61 seconds, SD = 0.41) conditions when the probe was visible [$t_{(14)} = 1.83$, $p < .04$, one-tailed]. Additionally, participants rated their responses less confidently as the number of suppressed items increased (Figure 3C). The average participant confidence in the 3/0 condition (M = 70.24 % confidence, SD = 12.62) differed from participant confidence in the 3/2 condition (M = 65.30 % confidence, SD = 14.00) at a statistically significant level [$t_{(14)} = -2.47$, $p < .01$, one-tailed]. Finally, participants indicated a PAS value of one 91.7% of the time.

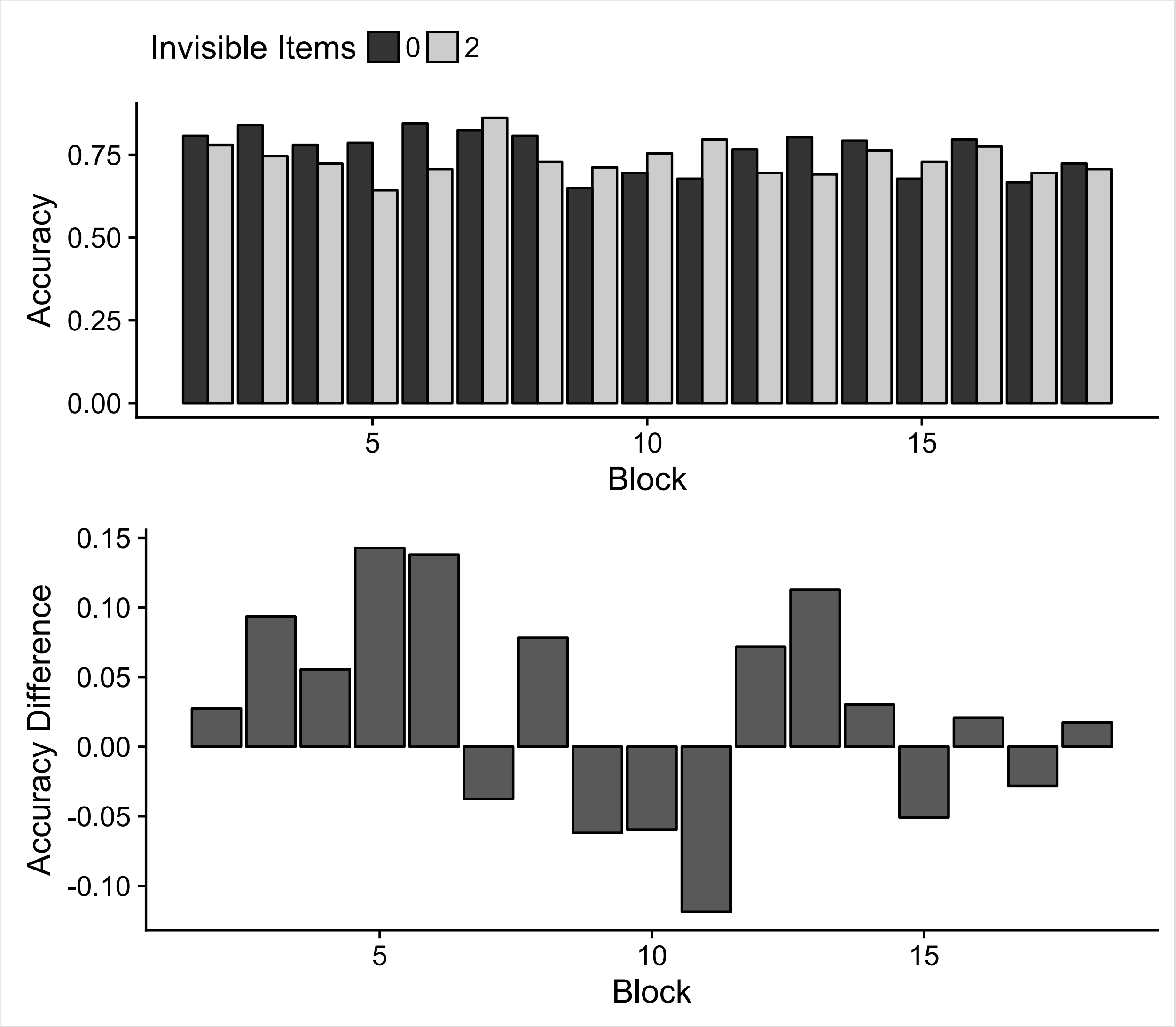

Figure 2. The interference effect as a function of time in the experiment. The top chart compares participant accuracy (proportion correct) in the 3 visible 0 invisible condition with the 3 visible 2 invisible condition across blocks. The bottom chart makes this relationship clear by plotting the difference in accuracy between conditions. This reveals that the interference effect became less pronounced over time.

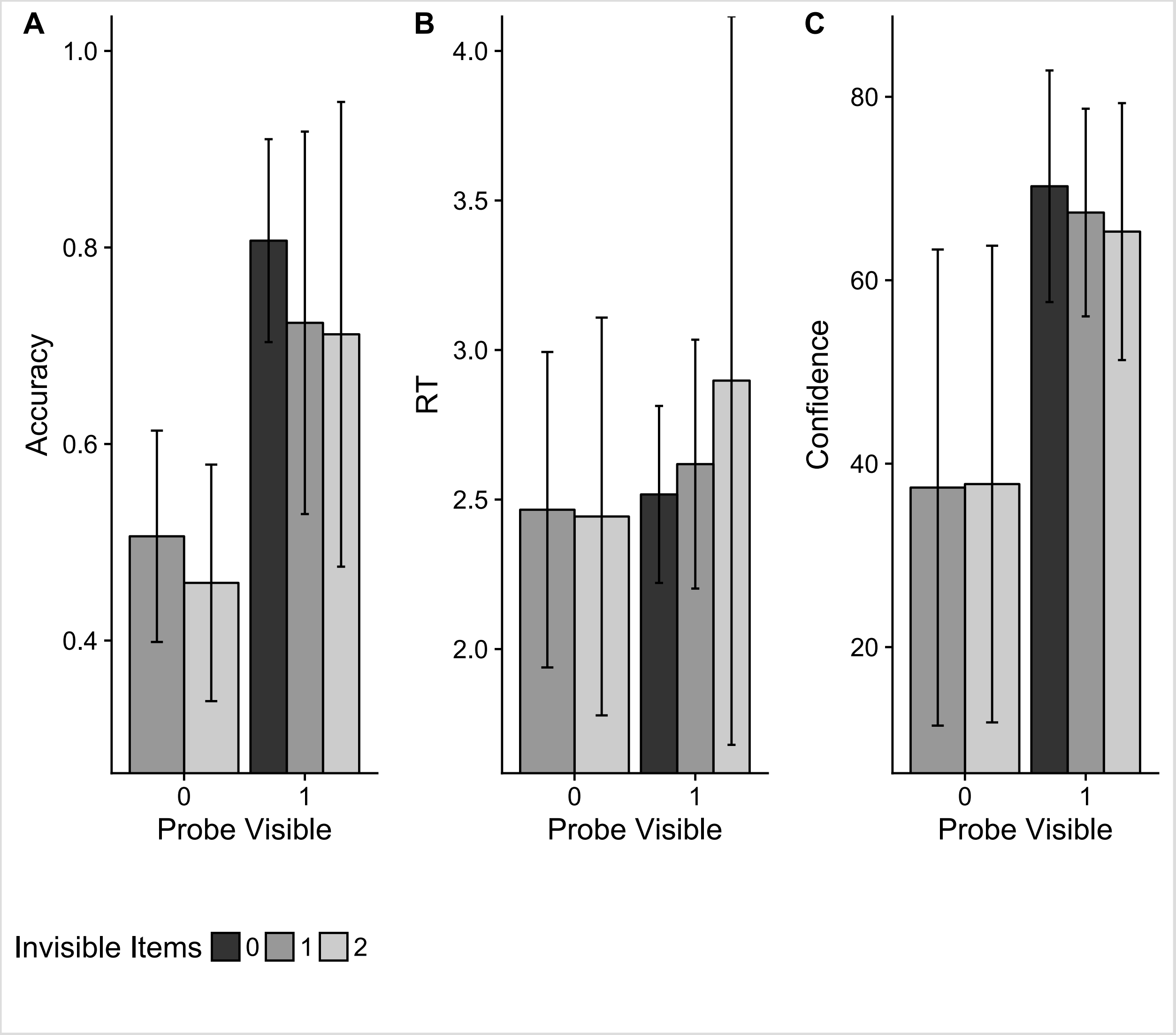

Figure 3. Participant performance across conditions over blocks two through eight. Probe Visible indicates whether the memory probe corresponds to an item which was consciously observable to the participant. Chart A shows accuracy results (proportion correct) indicating change detection for visible items was impaired by the presence of suppressed items. Participant accuracy was approximately at chance levels for invisible items. Chart B indicates that reaction time increased as the number of suppressed items increased in the visible probe condition, while chart C shows that participant confidence was higher in the visible probe condition when

compared with the invisible probe condition. Chart C also indicates that participants rated their responses less confidently when more invisible items were present.

Discussion

This study explored the possibility that unconsciously perceived visual information can take up space in WM as measured by reduced accuracy detecting changes in consciously perceived visual information. This is motivated by work suggesting that unconscious visual information can be retained in VWM (Bergström & Erikkson, 2015), and a recent series of experiments demonstrating an interference effect in which unconscious visual information interfered with retention of conscious items (Underwood, 2018). The purpose and experimental design of the present study was modeled closely on that of Underwood (2018), and sought to replicate findings from that work suggesting an interference effect is present.

We evaluated the hypothesis that unconscious information demands WM capacity, postulating that as the number of unconscious memory items increased, accuracy in detecting changes in conscious items would decrease. Results did not support the hypothesized interference effect, at least not when all blocks in the study were included in the analysis. However, we did observe an interference effect during early blocks, and a general decrease in the degree of this effect as the experiment progressed (Figure 2). Including only the first 6 blocks in analysis did yield a statistically significant effect in the hypothesized direction (Figure 3). This suggests that, if this effect exists, it may be influenced by motivation, fatigue, or other factors which change as the experiment progresses. Suppression from awareness appeared to be successful, given that our findings did not indicate that participants could recall items at above chance accuracy. These results were contrary to wan was reported previously (Bergström &

Erikkson, 2015; Pan, Cheng, & Luo, 2012; Pan, Lin, & Soto, 2014; Soto, Mäntylä, & Silvanto, 2011).

We also hypothesized that reaction time for visible probes would increase and response confidence would decrease as the number of invisible items increased. However, as with the findings for accuracy, these results did not show a significant effect when all blocks were included in analysis. Limiting analysis to initial blocks did reveal a statistically significant effect in the hypothesized direction–participants responded more slowly and less confidently as the amount of unconscious information increased. These findings replicate those reported in Underwood (2018), and reveal that unconscious information can influence how participants complete the task, at least in early blocks of the experiment. Analysis of results with Gestalt cues in relation to task accuracy was not included in this report. Therefore, we forgo discussing findings supporting or disconfirming that hypothesis.

One limitation of this study is that the participant attrition rate was very high–50 percent of subjects who completed the experiment were included in the analysis. This was due to exclusion criterion. Nearly all of the subjects excluded from analysis did not meet the minimum accuracy criteria of 65% in the 3 visible, 0 invisible item condition. Underwood (2018) reported a similar attrition rate, which included around 60% of the total data collected. This presents the practical consideration of lower power in statistical analysis, and prompts a consideration of (a) whether the exclusion criteria were too strict, (b) the task was too difficult or long, or (c) a different metric for capturing task engagement could be established. Additional analysis could be conducted investigating whether attrition is due to low VWM capacity, or low motivation to complete the task. If attrition is due to low VWM capacity, additional work could be done to investigate whether capacity is tied to the expression of the interference effect. A second limitation of this work is that it does not consider the fidelity of the representation in VWM, as participants are only asked to specify whether the memory item changed or stayed the same. Modifying the task to probe participants on subtler changes of a cue could provide information regarding the fidelity of the memory representation.

Though this study did not conclusively show that unconscious information can be stored in VWM, it does indicate that suppressed items can alter participant responses in some contexts. This indicates that the relationship between working memory and consciousness may be more nuanced than previously thought. Researchers in the field of consciousness research and memory research could both benefit from this information, as results may indicate a relationship between the two systems. A more conclusive finding would also hold relevant implications for applied research concerning computer user experience and user interaction. If unconsciously perceived information can impact processing and storage of conscious information, this would underscore the importance of clean, minimal user interfaces which do not unnecessarily tax working memory loads.

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