THE CAPACITY OF VISUAL WORKING MEMORY DURING VISUAL SEARCH

by

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Dedication

The time and effort that went into this dissertation are dedicated to the small army of supporters that have been with me every step of the way. To my parents, Tom and Melanie King, who encouraged me to follow my passion, to be true to myself, and to always take pride in my work. To Taylor Brandy, who showed me unconditional love, and who has given me the happiest years of my life. And finally to Brooke Macnamara, who always believed in me and never let me stop growing, both as a scientist and as a human. None of this would be possible without all of you. Thank you.

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The Capacity of Visual Working Memory During Visual Search

Abstract

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How many items can we store in visual working memory while simultaneously conducting a visual search? Previous research has proposed that only one visual working memory representation can be activated to influence attention directly, whereas other visual working memory representations are accessory items which have little influence on visual selection. However recent findings have suggested otherwise, specifically that two visual working memory representations can capture attention and interfere with concurrent visual search (Chen & Du, 2017). Across a series of studies, I investigated these findings further, and tested what the capacity of visual working memory is during visual search. The results from these studies suggest that multiple items held in visual working memory can capture attention and interfere with visual search. Specifically, I find that the capacity may be capped at two or three representations that can be simultaneously activated during search to guide attention, and that simplifying memoranda to a single feature does not increase capacity.

In everyday life, people struggle with the task of looking for an object in a crowded visual environment. Whether it is looking for a parking spot in a garage, searching a journal article for a specific statistic, looking for car keys on a messy desk, or simply looking for a friend among a large crowd of people. This behavior is known by cognitive psychologists as *visual search*, and the underlying components of this task have been studied by researchers for years (see e.g., Treisman, 1982).

One of the underlying components that influence our ability to conduct visual search, is visual working memory. Many of the major theories of attention propose that visual working memory plays a significant role in deploying attention and biasing perceptual processing toward target memory items during visual search (Chen & Du, 2017; Desimone & Duncan, 1995; Woodman, Vogel, & Luck, 2001). These theories, taken together, have led researchers to propose two likely ways in which visual working memory might be involved in visual search (Woodman et al., 2001).

The first way visual working memory may be involved in visual search is by template maintenance (Desimone & Duncan, 1995). That is, we might hold in mind the type of stimuli for which we are searching. We then search for targets that match the maintained template.

A second way visual working memory may be involved in visual search is by storing detected targets in memory (Duncan, 1980). Some researchers have suggested that the transfer of an item to visual working memory occurs automatically when attention is focused on an item (e.g., Cowan, 1997). This means that holding a set of items in working memory is achieved by first visually attending to these objects. Thus, the limited capacity of working memory during visual search is a direct result of the limited number of items that can be simultaneously attended.

Researchers have suggested that humans, on average, can hold 3–5 items in working memory at a time (Cowan, 2001; Luck & Vogel, 1997). However, this amount is reduced when attentional resources are simultaneously being used, such as when one is actively holding information in mind while simultaneously conducting a visual search (Cowan, 2001).

In line with this, other researchers have proposed that only one visual working memory representation can be actively attended to in the focus of attention at one time (McElree, 2001; van Moorselaar, Theeuwes, & Olivers, 2014). For example, McElree (2001) used two variants of an *n*-back task where study letters were sequentially presented in the center of a screen. After a mask was presented, the test letter was then presented in the same region as the study list. Participants responded that either the test item had or had not appeared in the *n*-back position of the list of sequentially presented letters. The first variant of this task used was the standard 3-back, in which individuals were required to respond positively to a test item only if it occurred 3 items back. This condition was referred to as 3-back *exclusion*, because individuals were required to exclude all positions other than 3-back. The second variant, termed 3-back *inclusion*, required participants to respond positively to all items up to and including 3-back. They hypothesized that if the *n*-back task is performed by actively maintaining the *n*-back item within the focus of attention, then the 3-back *inclusion* condition would require individuals to maintain three items, instead of one, within the focus of attention. It was predicted that performance would suffer with the additional attentional demands in the *inclusion* condition. In other words, reaction times in the 3-back *exclusion* condition task should be faster than the 3-back *inclusion* condition. However, if three items are within the capacity of attention, then no difference in reaction times should be found, because an individual could respond correctly if the test item matched any of the three items within the focus of attention. McElree (2001) found that retrieval speed was significantly faster in the 3-back *exclusion* task than in the 3-back *inclusion* task. They concluded that the advantage for the *exclusion* task involved the role of limited capacity control processes that avoided the need for a memory search process, by maintaining a target item within the focus of attention. Their results suggest that three sequentially presented items cannot be reliably maintained in focal attention. In other words, attention could be concurrently allocated to just one visual working memory representation.

More recent research has since introduced two types of visual working memory representations (Olivers, Peters, Houtkamp, & Roelfsema, 2011). One type is an *active* memory item that has direct access to perception, thus serving as an attentional template. The other type involves *accessory* memory items which are passively stored in visual working memory, and thus exert little influence on visual selection. According to this research, only one item in visual working memory at a time can serve as the active attentional template (van Moorselaar et al., 2014). Consistent with this, a target template item during a visual search consumes the only active slot in visual working memory when targets vary from trial to trial. According to this research, an irrelevant stimulus that matches other accessory working memory contents does not interfere with concurrent visual search because the capacity of the active memory store is already consumed by the target template item (Woodman & Luck, 2007). For example, before a trip to the grocery store, a person may hold images of the items they plan to buy in memory. However, before leaving their home for the store, they would need to conduct a visual search for their car keys. Here, the car keys become an *active* memory item, while the images of grocery products are *accessory* memory items. While looking for the keys, if a stimulus resembling one of the grocery items crosses their visual field, it would not interfere the visual search.

However, when the target template item is constant from trial to trial, this representation is eventually stored in long term memory instead of actively stored in visual working memory, allowing another item in visual working memory to become automatically activated to guide attention (Drew, Boettcher, & Wolfe, 2016; Reinhart & Woodman, 2015; Woodman, Carlisle, & Reinhart, 2013). That is, if participants are required to memorize two colors in visual working memory, a distractor matching either of those colors would have no influence on concurrent visual search because they are no longer active in working memory (van Moorselaar et al., 2014). For example, if one must search for their car keys on a repeated basis, the image for their car keys should eventually get transferred from active working memory to a long-term memory representation, allowing an accessory memory item to fill the active memory slot. In this case, a visual search for keys before a grocery store trip could be interfered by the presence of a stimulus resembling one of the memorized grocery items.

There is a fair amount of research on multiple target searches that supports the idea that only a single item in visual working memory can be active at a time. Many of these studies (i.e., Ort, Fahrenfort, & Olivers, 2017, 2018; Ort, Fahrenfort, Ten Cate, Eimer, & Olivers, 2019; van Moorselaar et al., 2014) report switch costs and limits to attentional selection with more than one search target. For example, Ort et al. (2017, 2018) asked whether multiple objects in visual working memory can be prioritized at the same time, by having participants search for two targets among distractors simultaneously. They found only small costs associated with preparing for selecting two objects (i.e., holding both items in visual working memory), but substantial costs when engaging in selection (i.e., conducting the visual search for both objects). These results give the impression that while more than one item can be stored in visual working memory in preparation for search, there seems to be a cost for actually searching for these representations, suggesting that participants can only activate one visual working memory item for search at a time.

If correct, this proposed single active visual working memory representation might reflect a fundamental bottleneck in human information processing (Chen & Du, 2017; Drew et al., 2016). However, recent findings that irrelevant stimuli matching either of two target colors can involuntarily capture attention suggest otherwise (Adamo, Pun, Pratt, & Ferber, 2008; Du & Abrams, 2012; Du, Zhang, & Abrams, 2014). These findings show that visual search can be under simultaneous control of two target templates, in the form of single featured color stimuli (Beck, Hollingworth, & Luck, 2012). While these color targets change from trial to trial, there are only two possible target colors, resulting in two constant target templates being stored in visual working memory (Irons, Folk, & Remington, 2012) but quickly moving to long term memory (Drew et al., 2016; Reinhart & Woodman, 2015; Woodman et al., 2013). Thus, these findings may not actually display two active representations in visual working memory.

By using unique target memoranda with multiple features (color and texture) that varied from trial to trial—so theoretically would be stored as visual working memory representations and not transferred to long term memory—Chen and Du (2017) investigated whether two visual working memory representations could simultaneously guide attention and interfere with concurrent visual search for a target that is not one of the memoranda held in visual working memory. They found that two visual working memory representations indeed captured attention and interfered with concurrent visual search. In addition, each of these two visual working memory representations interfered with concurrent visual search as much as a single cued representation. Thus, Chen and Du (2017) argue that a capacity of two visual working memory items can simultaneously control attention during visual search.

Pilot Study

In a replication of Chen and Du's (2017) Experiment 2, I first tested whether I could reproduce the evidence that two items simultaneously held in visual working memory could bias attention during visual search. This study was pre-registered on the Open Science Framework (https://osf.io/8m4nj). See Figure 1 for trial sequences.

Methods

Participants. Chen and Du's (2017) Experiment 2 included 40 participants. We recruited 46 participants through the Case Western Reserve University SONA system subject pool based on our preregistered data collection stopping rule. Following our exclusion criteria, two participants' data were removed because their accuracy on the memory task was below 60%. The study was performed in accordance with the Declaration of Helsinki and was approved by the Case Western Reserve University IRB review board. Participants gave their written informed consent to participate in the study. They received partial course credit or extra credit for their participation.

Materials and equipment. The experiment was controlled using the open source application PsychoPy (Peirce, 2007) on a 2014 9020 all-in-one Dell Optiplex desktop computer with a 15-in. CRT monitor (90-Hz refresh rate) at a viewing distance of approximately 60 cm. All analyses were completed using JASP statistical software (JASP TEAM, 2019).

Visual task description and procedure.

Memoranda. Each trial began with two circles (each with a radius of 0.6°) appearing on the screen for 500 ms that the participants were asked to remember. Each circle consisted of one of 12 possible color-texture combinations. The four colors included: red (RGB: 250, 20, 0), green (RGB: 0, 170, 0), yellow (RGB: 220, 200, 20), or blue (RGB: 0, 90, 200). Each circle also consisted of one of three types of texture (checkerboard, striped, or reticulation).

In the one-memory-item condition, a gray arrow (RGB: 85, 85, 85; 0.8° in width, 1.6° in length) pointing either to the right or left, indicated to participants that they were supposed to only memorize that specific circle. In the two-memory-item condition, no arrow appeared, indicating that participants were to memorize both circles. Each presented circle was randomly selected from a pool of 12 possible combinations of four colors and three textures.

Search. Following the appearance of the two circles, the screen was blank for 300ms, and then participants were presented with a search display. The search display consisted of a gray diamond (1.2° in size) and seven circle distractors (each with a radius of 0.6°). They were placed on the rim of an imaginary circle (with a radius of 8°), which was centered on the fixation. The diamond contained a black target letter that could be either an “N” or an “M” (0.38° in size). Participants were instructed to indicate whether the diamond contained an “N” or “M” as fast as possible, by hitting the “N” or “M” key on the keyboard. The search display remained on the screen until participants selected “N” or “M.” Each gray circle on the search display contained a symbol resembling an hourglass. One of the seven circles served as a distractor (see Figure 1). There were four distractor types. See Table 1.

Table 1.
Pilot Study Distractor Types

Distractor Condition	Description
	Single-Item Memory Condition
Cued distractor	Circle’s color and texture are the same as the cued item
Uncued distractor	Circle’s color and texture are the same as the uncued item
New Distractor	Circle’s color and texture are different from the cued and uncued items
No Distractor	No circle with color or texture is present
	Two-Item Memory Condition
M1 Distractor	Circle’s color and texture are the same as the item presented on the left
M2 Distractor	Circle’s color and texture are the same as the item presented on the right
New Distractor	Circle’s color and texture are different from the cued and uncued items
No Distractor	No circle with color or texture is present

Memory test. Following the search display, a blank screen appeared for 500ms. Next, a probe screen appeared where the participants were tasked with responding whether or not one of a set of 8 probe circles matched one of the memoranda. Probe circles could share the same color but differ in texture or share the same texture but differ in color as the memorized item, therefore participants could not use a single feature for memory task. In the single-item memory condition, the cued item was only presented on half of the trials, while the uncued item never appeared as a probe circle. However, in the two-memory item condition, in which participants were instructed to memorize both items, the “M1” and “M2” items (the first-position memoranda and the second-position memoranda) were present in the probes with equal probability for 50% of the trials. They never occurred in the probe display simultaneously. See Figure 1.

Task procedure. The order of the two memory conditions was counter-balanced across participants. Each participant completed two single-item memory sets and two two-item memory sets. Conditions were counterbalanced. There were 24 practice trials per condition, and 192 experimental trials per condition (48 trials per set). Each distractor condition (Cued, Uncued, New, None; M1, M2, New, None) was presented an equal number of times within each memory set, in a random order.

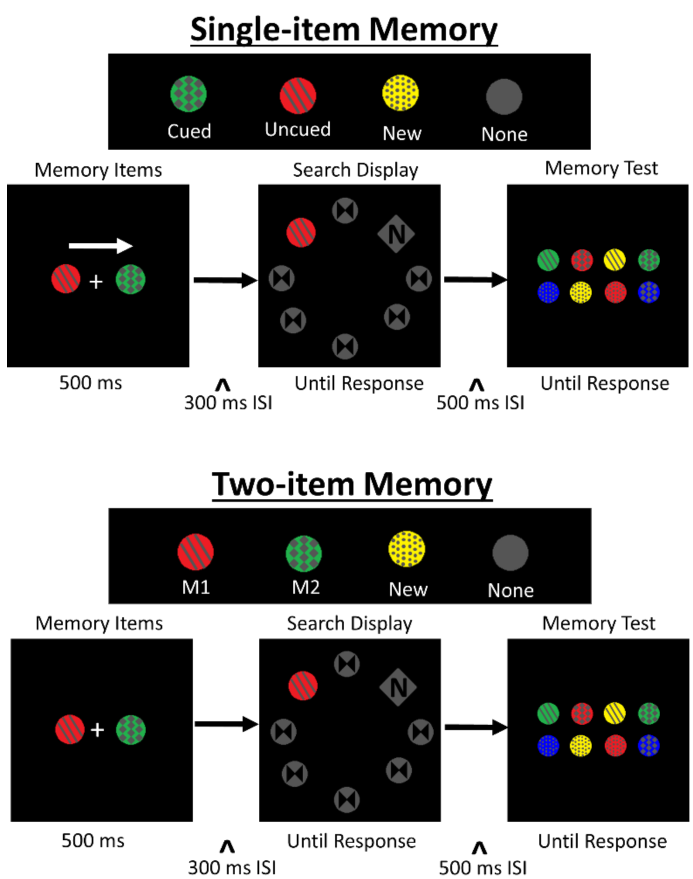

Figure 1. Trial display with four different possible distractor conditions per trial for the single-item memory, and two-item memory conditions.

Results. In line with Chen and Du's (2017) results, in the single memory condition, there was a main effect of distractor condition, $F(3, 129) = 82.54$, $p < .001$, $\eta_p^2 = .66$. Further pairwise comparisons with Bonferroni adjustments revealed that the reaction times (RTs) of the Cued distractor were significantly longer than the RTs of the Uncued distractor, the New distractor, and the No distractor conditions (all $ps_{bonf} < .01$). Also, the RTs of the Uncued condition were significantly longer than the RTs of the No distractor condition ($p_{bonf} < .01$, $d = 1.05$), and the New distractor condition produced significantly longer RTs than the No distractor condition ($p_{bonf} < .01$, $d = 1.45$). See Figure 2.

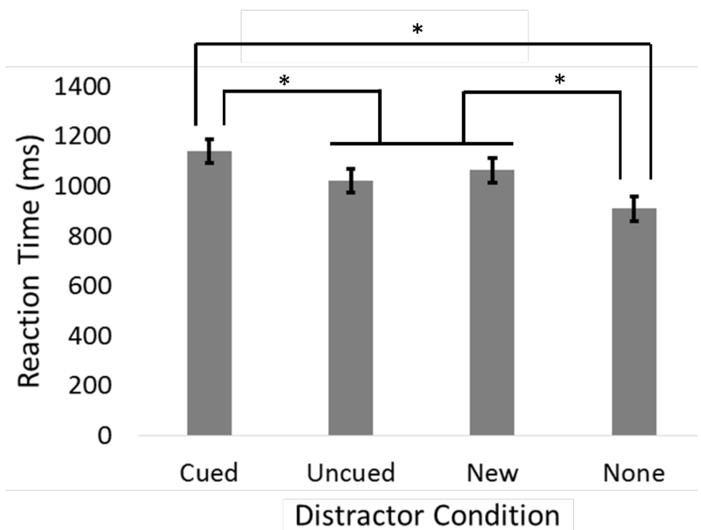

Figure 2. RTs for the search display as a function of distractor condition in the single cued memory item condition. Error bars represent standard errors of the mean. * = statistically significant difference in RTs at $p < .05$.

In the Two-item Memory condition, there was a main effect of distractor condition, $F(3, 129) = 62.54$, $p < .001$, $\eta_p^2 = .59$. Further pairwise comparisons with

Bonferroni adjustments revealed that the RTs from the M1 distractor and the M2 distractor did not differ from one another (p_{bonf} = .137). The RTs from the M1 distractor and the M2 distractor were both significantly longer than the RTs of the new distractor condition, $p_{bonf} < .001$, $d = 0.99$, and $p_{bonf} < .001$, $d = 1.06$, respectively, and significantly longer than the RTs of the no distractor condition, $p_{bonf} < .001$, $d = 1.34$, and $p_{bonf} < .001$, $d = 1.48$, respectively. Additionally, the new distractor condition produced significantly longer RTs than the no distractor condition, $p_{bonf} < .001$, $d = 0.76$. See Figure 3.

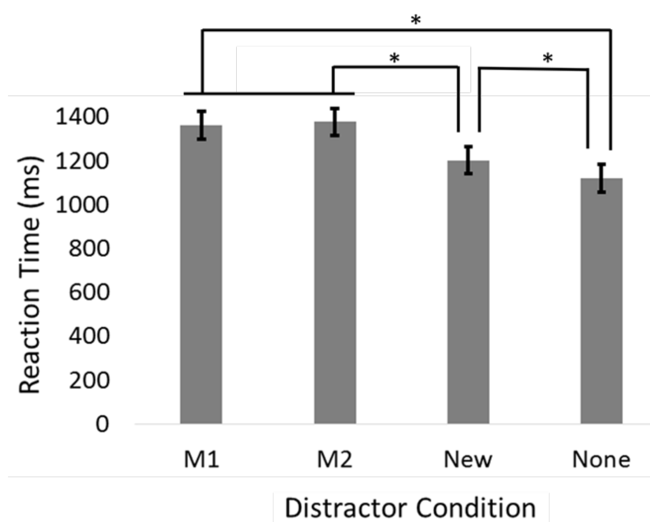

Figure 3. RTs for the search display as a function of distractor condition in the two-item memory condition. Error bars represent standard errors of the mean. * = statistically significant difference in RTs at $p < .05$.

A memory-capture index (MCI; Chen & Du, 2017) was calculated to measure the interference caused by distractors. The MCI is calculated by taking the difference between the mean reaction time of the Cued condition and the New condition, divided by 0.5. This value is then multiplied by the sum of the mean reaction time from the

Cued condition and the New condition [MCI = (RTcue-RTnew)/0.5*(RTcue + RTnew)].

According to Chen and Du (2017), if only one visual working memory representation can be activated, when visual working memory is loaded with two stimuli there should be no memory-driven attentional capture (i.e., no significant MCI effect). That is, if participants are merely alternating whether M1 or M2 is the sole active representation, then the combined MCI for M1 and M2 (M1 + M2) should not be significantly different than the MCI of a single cued memory item. Additionally, if only one visual working memory representation can be activated and there is a bias toward one of the memoranda, the MCI of one of them (M1 or M2) should be smaller than that for a single cued memory item.

However, if M1 and M2 in the two memory items condition are both being held in visual working memory, the MCI for each should be comparable to the Cued distractor in the single cued memory item condition and the combined MCI for M1 and M2 (M1 + M2) should be significantly larger than the MCI of a single cued memory item. The combined MCI effect of the M1 and M2 distractors in the two-item memory condition was significantly larger than that of the Cued distractor in the single-item memory condition, (Mean Difference = 1.16, $p < 0.001$).

Discussion. In the single-item memory condition, participants were more distracted, as indicated by slower RTs, when the cued item appeared in the search display than when the uncued item appeared in the visual search. The uncued item was no more distracting than a novel item. These results suggest that participants were maintaining the cued item in visual working memory and not maintaining the uncued item in visual working memory.

In the two-item memory condition, participants were more distracted when either of the two cued items appeared in the search display than when a novel item appeared in the search display. There was no difference in RTs between the two cued items. These results suggest that participants were maintaining two items in visual working memory. Further, results from the MCI analysis suggest that these two items were simultaneously maintained in visual working memory. The pilot study replicated Chen and Du’s (2017) finding that not one, but two visual working memory representations can be simultaneously activated to guide attention during visual search.

It is also important to note that there are two minor differences in this pilot and Chen and Du’s (2017) Experiment 2. In the present experiment, I included reaction times in the analysis for all trials, regardless if the participant correctly or incorrectly recalled the visual working memory item, whereas Chen and Du (2017) only included correct trials. I also ran analyses with correct trials only, and it did not change the pattern of results. Also, Chen and Du (2017) trimmed their reaction time data by three standard deviations from each participant’s mean reaction time, whereas I did not do this.

Experiments

The current dissertation aimed to build off the pilot replication study. I conducted three experiments to test whether visual working memory capacity can extend to more than two items during visual search, and to investigate whether or not the results changed based on the number of features of visual working memory stimuli. The experiments followed a specific order, such that the findings of Experiment 1 determined what Experiment 2 would investigate, and so on (see Figure 4). Each subsequent study begins with a figure showing the experiment's place in this decision tree (Figures 5, 9, and 13).

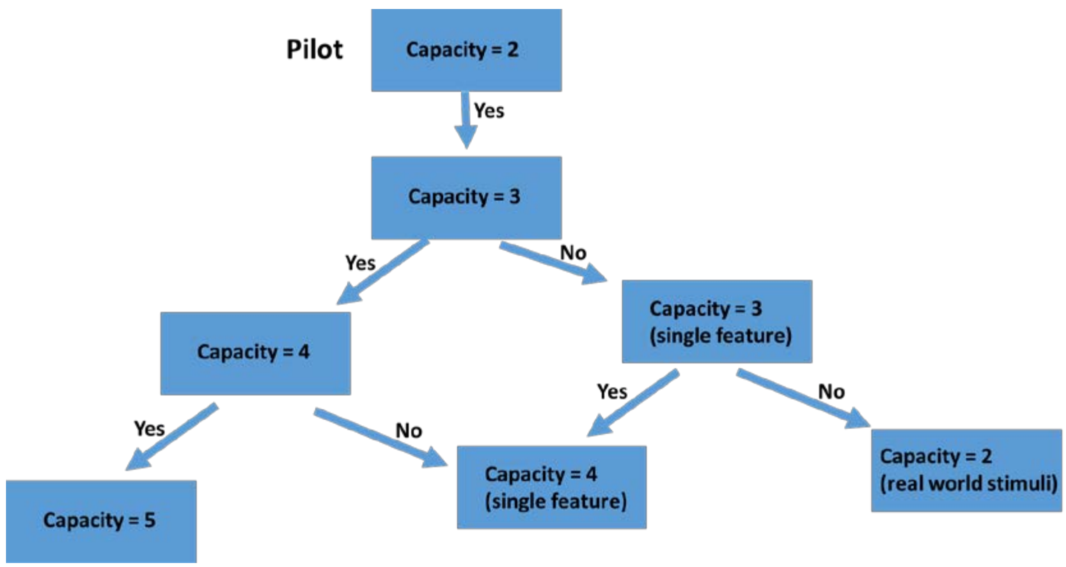

Figure 4. Proposed experimental sequence. Yes = support for the hypothesis (e.g., capacity of at least 3 items). No = lack of support for the hypothesis (e.g., no support for a capacity of 3 items). Thus, the final dissertation is composed of three total experiments.

Experiment 1

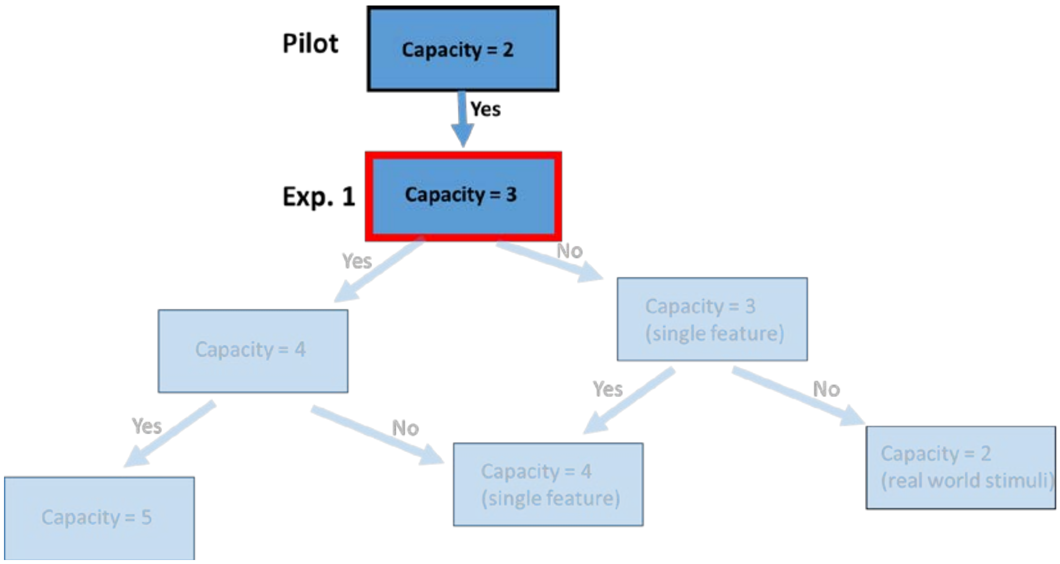

Figure 5. Experiment sequence, Experiment 1

In the pilot replication study, I confirmed Chen and Du's (2017) finding that two visual working memory representations can simultaneously control attention. However, it had not been tested whether two items represent the full capacity of visual working memory during visual search. To follow up on these results, Experiment 1 investigated whether two items is the limit, or if the capacity can extend to three items in visual working memory that simultaneously control attention during visual search. See Figure 6 for trial sequences.

Methods

Participants. Based on my data collection stopping rule, sixty participants were recruited through the Case Western Reserve University SONA system subject pool. However, two participants were excluded because their accuracy on the memory task was below 60%, and two participants were excluded due to uncooperative behavior during the experiment. The study was performed in accordance with the Declaration of Helsinki and was approved by the Case Western Reserve University IRB review board. Participants gave their written informed consent to participate in the study. They received partial course credit or extra credit for their participation.

Materials and Equipment. The experiment was controlled using the open source application PsychoPy (Peirce, 2007) on a 2014 9020 all-in-one Dell Optiplex desktop computer with a 15-in. CRT monitor (90-Hz refresh rate) at a viewing distance of approximately 60 cm. All analyses were completed using JASP statistical software (JASP TEAM, 2019).

Visual task description and procedure. The methods are identical to the methods of the pilot replication study except as described below.

Memoranda. In the two-memory-item condition, three memoranda were presented at the beginning of each trial and were displayed for 500ms. An outline surrounded two of the three circles indicating that participants were supposed to only memorize those specific circles (see Figure 6). The outline always surrounded the upper two circles, and participants were instructed to only memorize the outlined circles. In the three-memory-item condition, three memoranda were presented at the beginning of each trial and were displayed for 750ms. An outline surrounded all of the circles indicating that participants were supposed to memorize all the circles.

Search. The search was identical to the pilot replication study except for the distractor conditions. See Table 2. In the M1 distractor condition, the circle's color and texture was the same as the memorized item appearing in the first (top left) position. In the M2 distractor condition, the circle's color and texture was the same as the memorized item in the second (top right) position. In the M3 condition, the circle's color and texture was the same as the memorized item in the third (lower) position. In the new-distractor condition, the circle was a combination of color and texture that was not part of the memoranda. In the no-distractor condition, all seven circles were gray.

Table 2.
Experiment 1 Distractor Types

Distractor Condition	Description
	Two-Item Memory Condition
M1 distractor	Circle’s color and texture are the same as the item presented on the top-left
M2 distractor	Circle’s color and texture are the same as the item presented on the top-right
Uncued distractor	Circle’s color and texture are the same as the uncued item
New Distractor	Circle’s color and texture are different from the M1, M2, and uncued items
No Distractor	No circle with color or texture is present
	Three-Item Memory Condition
M1 Distractor	Circle’s color and texture are the same as the item presented on the top-left
M2 Distractor	Circle’s color and texture are the same as the item presented on the top-right
M3 Distractor	Circle’s color and texture are the same as the item presented on the bottom
New Distractor	Circle’s color and texture are different from the cued and uncued items
No Distractor	No circle with color or texture is present

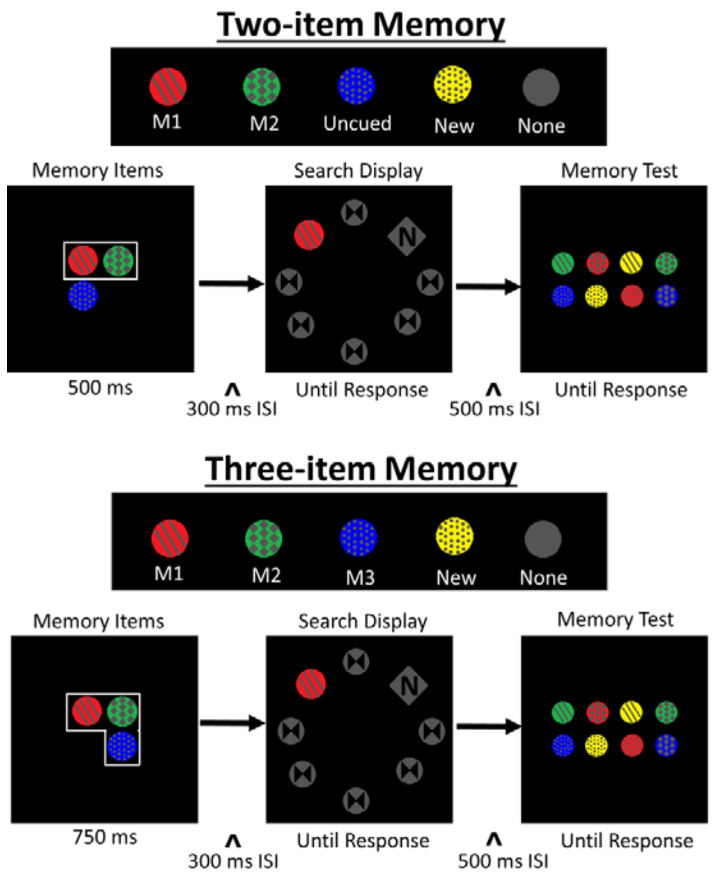

Figure 6. Trial display with five different possible distractor conditions per trial for the two-item memory, and three-item memory conditions.

Results. In the two-item memory condition, there was a main effect of distractor condition, $F(4, 220) = 19.70$, $p < .001$, $\eta_p^2 = .26$. Pairwise comparisons with Bonferroni adjustments revealed that the RTs of the M1 distractor and the M2 distractor did not differ significantly from one another, ($p_{bonf} = .235$) and the RTs of both the M1 and M2 distractor conditions were significantly longer than the RTs of the Uncued distractor condition ($p_{bonf} < .01$, $d = 0.39$, and $p_{bonf} < .01$, $d = 0.44$ respectively), the New distractor condition ($p_{bonf} < .001$, $d = 1.05$, and $p_{bonf} < .001$, $d = 1.14$ respectively), and the no distractor condition ($p_{bonf} < .001$, $d = 1.34$, and $p_{bonf} < .001$, $d = 1.40$ respectively). Also, the Uncued and the New distractor conditions both produced significantly longer RTs than the No distractor condition, ($p_{bonf} < .01$, $d = 0.26$, and $p_{bonf} < .001$, $d = 0.77$ respectively). See Figure 7. This was the same pattern of results revealed in Experiment 1's two-item memory condition.

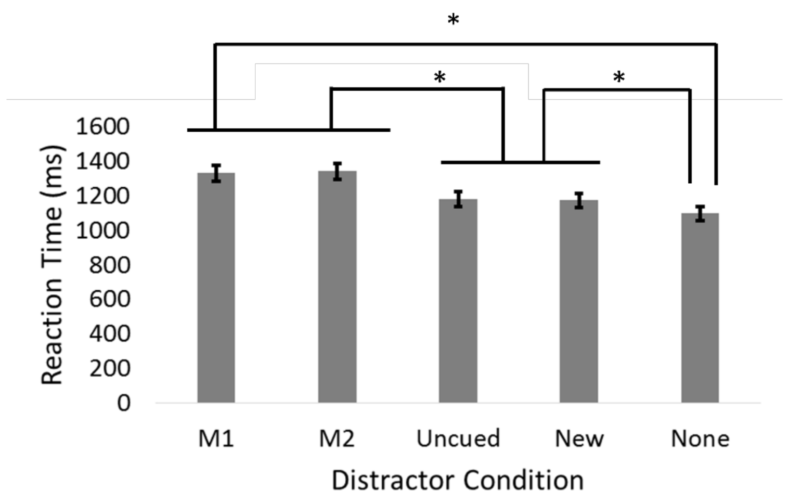

Figure 7. RTs for the search display as a function of distractor condition in the two-item memory condition. Error bars represent standard errors of the mean. * = statistically significant difference in RTs at $p < .05$.

In the three-item memory condition, there was a main effect of distractor condition, $F(4, 220) = 228.1$, $p < .001$, $\eta_p^2 = .80$. Pairwise comparisons with Bonferroni adjustments revealed that the RTs of the M1, M2, and M3 distractors were not significantly different from one another, all $ps_{\mathrm{bonf}} > .500$. The RTs of the M1, M2, and M3 distractor conditions were significantly longer than the RTs of the New distractor condition ($p_{bonf} < .001$, $d = 1.15$; $p_{bonf} < .001$, $d = 1.24$; $p_{bonf} < .001$, $d = 1.19$, respectively), and the no distractor condition, ($p_{bonf} < .001$, $d = 1.27$; $p_{bonf} < .001$, $d = 1.36$; $p_{bonf} < .001$, $d = 1.29$ respectively). The New distractor condition produced significantly longer RTs than the No distractor condition, $p_{bonf} < .001$, $d = 0.59$. See Figure 8.

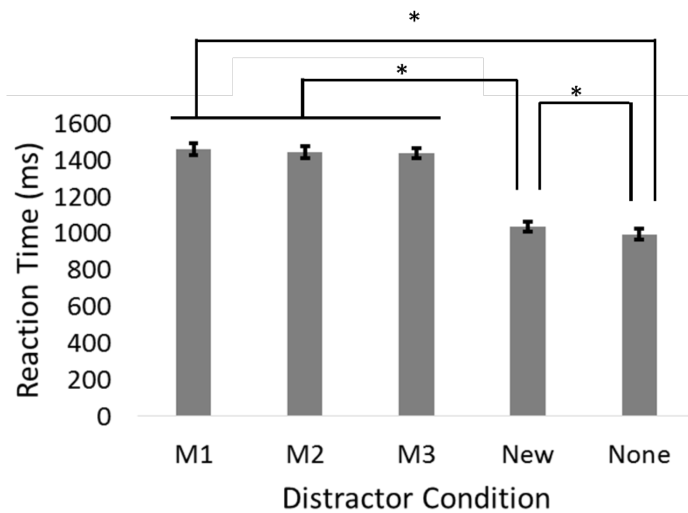

Figure 8. RTs for the search display as a function of distractor condition in the three-item memory condition. Error bars represent standard errors of the mean. * = statistically significant difference in RTs at $p < .05$.

A memory-capture index (MCI) was again calculated to measure the interference caused by distractors. An MCI value was calculated for M1, M2, and M3 distractor conditions in the three-item memory condition. These values were summed to create a combined MCI effect. The same was done for the combined MCI effect in the two-item memory condition. That is, a separate MCI value was calculated for the M1 and M2 distractor conditions and then these values were summed. The results of Experiment 1's MCI analysis suggests that all three representations were being maintained: the combined MCI effect of the M1, M2, and M3 distractors in the three-item memory condition was significantly larger than the combined MCI effect of the M1 and M2 distractors in the two-item memory condition (Mean Difference = 4.37, $p < .001$).

Discussion. The results of Experiment 1 suggest that not just two, but three representations were being maintained. The two-item memory condition replicated the results found in the pilot study, where the M1 and M2 distractor condition both had significantly longer RTs than the Uncued condition, and the uncued item was no more distracting than the new item. Further, the RTs associated with the M1 and M2 distractors were not significantly different from each other. These results suggest that participants were maintaining the two cued items in visual working memory while conducting visual search and were not maintaining the uncued item as directed.

The three-item memory condition extended these results, where the M1, M2, and M3 distractor conditions all had significantly longer RTs than the New conditions, while the M1, M2, and M3 conditions were not significantly different from one another. Additionally, the combined MCI effect of the M1, M2, and M3 distractors in the three-item memory condition was significantly larger than the combined MCI effect of the M1 and M2 distractors in the two-item memory condition (Mean Difference = 4.37, $p < .001$). These results suggest that participants were maintaining three items in visual working memory during visual search. Taken together, this experiment supports the hypothesis that there are multiple active slots in visual working memory, and that three visual working memory representations may be simultaneously activated to guide attention during visual search.

Experiment 2

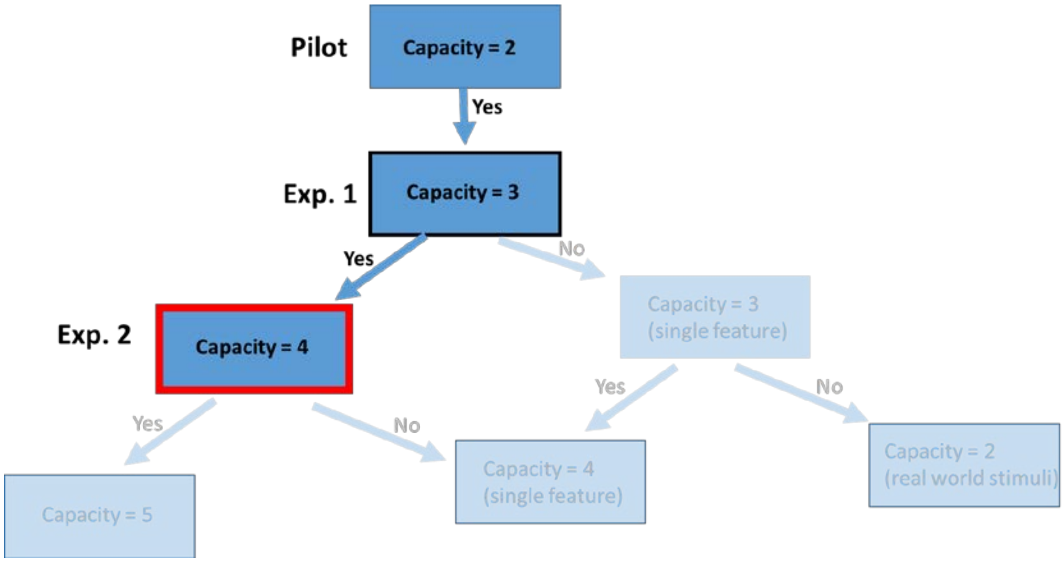

Figure 9. Experiment sequence, Experiment 2.

In Experiment 1, we demonstrated that not two, but three items held in visual working memory can capture attention. However, it has not been tested whether three items represent the full capacity of visual working memory during visual search. To follow up on these results, Experiment 2 investigated whether three items is the limit, or if the capacity can extend to four items in visual working memory that simultaneously control attention during visual search. See Figure 10 for trial sequences.

Methods

Participants. Based on my data collection stopping rule, sixty participants were recruited through the Case Western Reserve University SONA system subject pool. However, two participants were excluded because their accuracy on the memory task was below 60%. The study was performed in accordance with the Declaration of Helsinki and was approved by the Case Western Reserve University IRB review board. Participants gave their written informed consent to participate in the study. They received partial course credit or extra credit for their participation.

Materials and Equipment. The experiment was controlled using the open source application PsychoPy (Peirce, 2007) on a 2014 9020 all-in-one Dell Optiplex desktop computer with a 15-in. CRT monitor (90-Hz refresh rate) at a viewing distance of approximately 60 cm. All analyses were completed using JASP statistical software (JASP TEAM, 2019).

Visual task description and procedure. The methods are identical to the methods of Experiment 1 except as described below.

Memoranda. In the three-memory-item condition, four memoranda were presented at the beginning of each trial and were displayed for 750ms. An outline surrounded three of the four circles indicating that participants were supposed to only memorize those specific circles (see Figure 10). The outline always surrounded the upper two and bottom right circles, and participants were instructed to only memorize the outlined circles. In the four-memory-item condition, four memoranda were presented at the beginning of each trial and were displayed for 1000ms. An outline surrounded all of the circles indicating that participants were supposed to memorize all the circles.

Search. The search was identical to Experiment 1 except for the distractor conditions. See Table 3. In the M1 distractor condition, the circle's color and texture was the same as the memorized item appearing in the first (top left) position. In the M2 distractor condition, the circle's color and texture was the same as the memorized item in the second (top right) position. In the M3 condition, the circle's color and texture was the same as the memorized item in the third (bottom right) position. In the M4 condition, the circle's color and texture was the same as the memorized item in the fourth (bottom left) position. In the new-distractor condition, the circle was a combination of color and texture that was not part of the memoranda. In the no-distractor condition, all seven circles were gray.

Table 3.
Experiment 2 Distractor Types

Distractor Condition	Description
	<u>Three-Item Memory Condition</u>
M1 Distractor	Circle’s color and texture are the same as the item presented on the top-left
M2 Distractor	Circle’s color and texture are the same as the item presented on the top-right
M3 Distractor	Circle’s color and texture are the same as the item presented on the bottom
Uncued Distractor	Circle’s color and texture are the same as the uncued item
New Distractor	Circle’s color and texture are different from the cued and uncued items
No Distractor	No circle with color or texture is present
	<u>Four-Item Memory Condition</u>
M1 Distractor	Circle’s color and texture are the same as the item presented on the top-left
M2 Distractor	Circle’s color and texture are the same as the item presented on the top-right
M3 Distractor	Circle’s color and texture are the same as the item presented on the bottom-left
M4 Distractor	Circle’s color and texture are the same as the item presented on the bottom-right
New Distractor	Circle’s color and texture are different from the cued and uncued items
No Distractor	No circle with color or texture is present

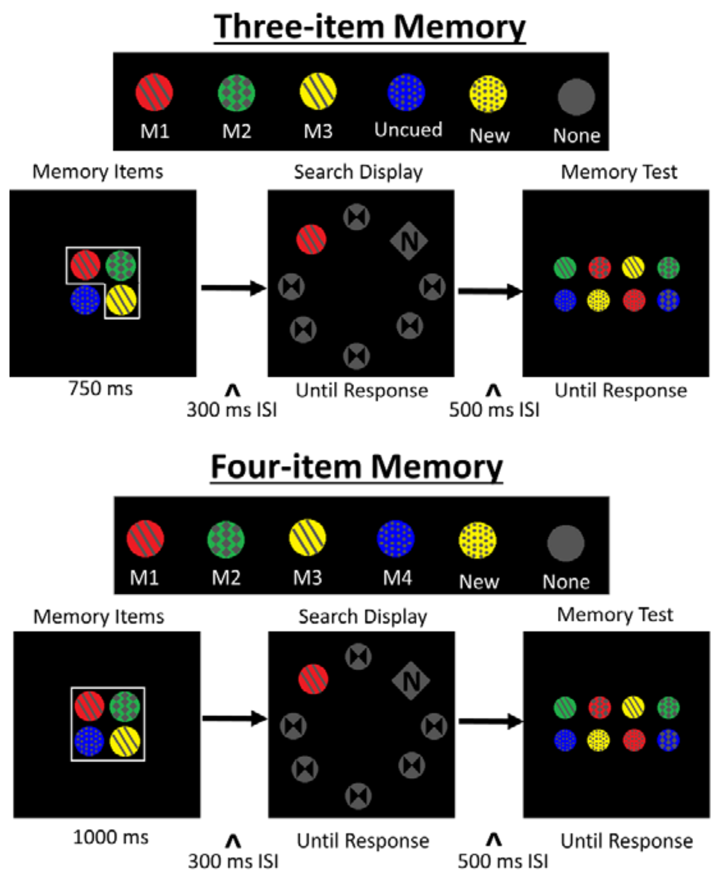

Figure 10. Trial display with six different possible distractor conditions per trial for the three-item memory, and four-item memory conditions.

Results. In the three-item memory condition, there was a main effect of distractor condition, $F(5, 285) = 4.86$, $p < .001$, $\eta_p^2 = .08$. Pairwise comparisons with Bonferroni adjustments revealed that the RTs of the M1, M2, M3, and New distractors were not significantly different from one another, all $ps_{bonf} > .300$. The RTs of the M1 distractor condition were significantly longer than the RTs of the Uncued distractor condition ($p_{bonf} < .01$, $d = 0.46$) and the No distractor condition ($p_{bonf} < .01$, $d = 0.51$). The M2, M3, Uncued, New, and No distractor conditions did not differ significantly from one another, all $ps_{bonf} > .07$. See Figure 11.

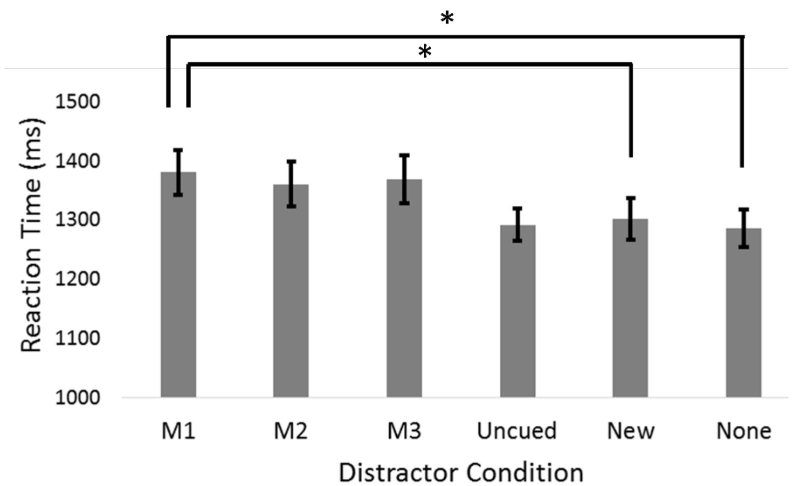

Figure 11. RTs for the search display as a function of distractor condition in the three-item memory condition.

In the four-item memory condition, there was a main effect of distractor condition, $F(5, 285) = 5.35$, $p < .001$, $\eta_p^2 = .09$. Pairwise comparisons with Bonferroni adjustments revealed that the RTs of the M1, M2, M3, M4, and New distractors were not significantly different from one another, all $ps_{bonf} > .225$. The RTs of the M1 distractor condition were significantly longer than the RTs of the No distractor condition ($p_{bonf} < .001$, $d = 0.82$). The RTs of the M3 distractor condition were significantly longer than the RTs of the No distractor condition ($p_{bonf} < .05$, $d = 0.43$). The RTs of the M4 distractor condition were significantly longer than the RTs of the New and the None distractor conditions ($p_{bonf} < .05$, $d = 0.46$, and $p_{bonf} < .001$, $d = 0.57$ respectively). The New distractor condition was not significantly different from the No distractor condition, $p_{bonf} > .500$. See Figure 12.

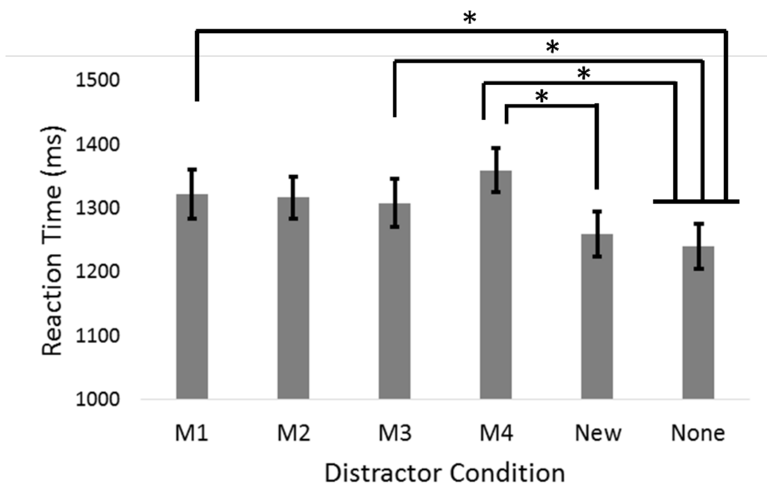

Figure 12. RTs for the search display as a function of distractor condition in the four-item memory condition.

A memory-capture index (MCI) was again calculated to measure the interference caused by distractors. An MCI value was calculated for M1, M2, M3, and M4 distractor conditions in the four-item memory condition. These values were summed to create a combined MCI effect. The same was done for the combined MCI effect in the three-item memory condition. That is, a separate MCI value was calculated for the M1, M2, and M3 distractor conditions and then these values were summed. The results of Experiment 2's MCI analysis do not suggest that all four representations were being maintained: the combined MCI effect of the M1, M2, M3, and M4 distractors in the four-item memory condition did not differ significantly from the combined MCI effect of the M1, M2, and M3 distractors in the three-item memory condition (Mean Difference = 0.29, p = .48).

Discussion. The three-item memory condition did not replicate the results found in Experiment 1. That is, the results of Experiment 2 do not suggest that three visual working memory representations were being maintained during search. While the M1, M2, and M3 distractor conditions were not significantly different from one another, only the M1 distractor condition had significantly longer RTs than the New and None conditions. This suggests that participants were not able to hold all three memoranda in memory. Alternatively, given the lack of significant difference between the cued items and the uncued item, it is possible that participants were attending to the uncued item in the three-item memory condition, thus effectively making this a four-item condition, and that participants are unable to maintain four items in memory.

The four-item memory condition also had mixed results. The M1, M3, and M4 conditions were significantly longer than the None condition, and only the M4 condition was significantly longer than the New condition. Additionally, the MCI analysis does not suggest that all four representations were being maintained. The combined MCI effect of the M1, M2, M3, and M4 distractors in the four-item memory condition did not differ significantly from the combined MCI effect of the M1, M2, and M3 distractors in the three-item memory condition (Mean Difference = 0.29, $p = .48$). These results suggest that while there are multiple active slots in visual working memory, the capacity may be capped at two or three representations that can be simultaneously activated during search to guide attention.

Experiment 3

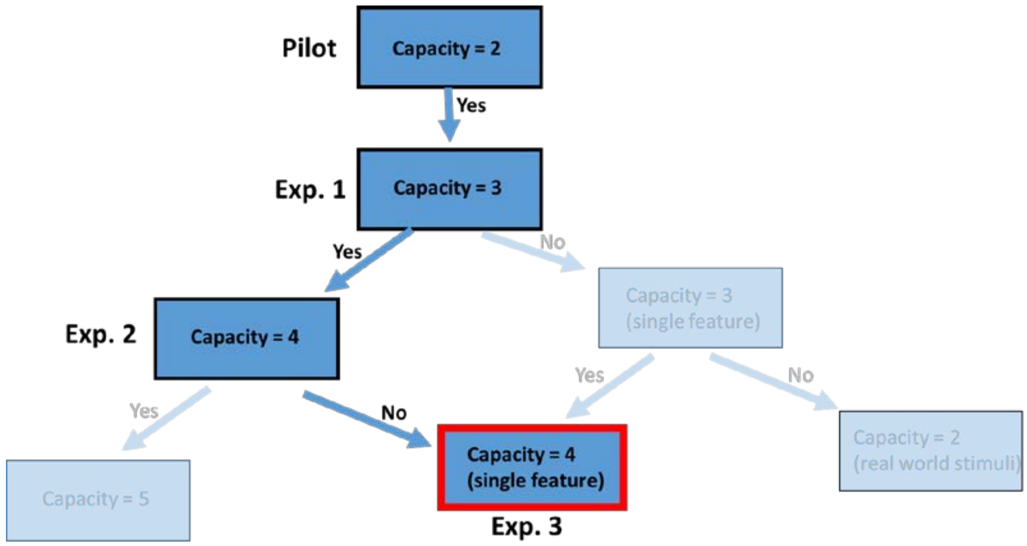

Figure 13. Experiment sequence, Experiment 3.

In Experiment 2, the results suggested that four items cannot be held in visual working memory during visual search. However, there may be a trade-off between the complexity of items and the total number of items that can be stored at a given time (Alvarez & Cavanagh, 2004). The stimuli used in my experiments up until this point consist of items that have dual features (i.e., color and texture). To follow up on these results, Experiment 3 investigated whether three items, using single feature stimuli (color only, no textures) is the limit, or if the capacity can extend to four items with single features in visual working memory. That is, this study replicated the methods of Experiment 2 with the exception of the stimuli being single-featured rather than dual featured. See Figure 14 for trial sequences.

Methods

Participants. Based on my data collection stopping rule, sixty participants were recruited through the Case Western Reserve University SONA system subject pool. However, one participant was excluded because their accuracy on the memory task was below 60%. The study was performed in accordance with the Declaration of Helsinki and was approved by the Case Western Reserve University IRB review board. Participants gave their written informed consent to participate in the study. They received partial course credit or extra credit for their participation.

Materials and Equipment. The experiment was controlled using the open source application PsychoPy (Peirce, 2007) on a 2014 9020 all-in-one Dell Optiplex desktop computer with a 15-in. CRT monitor (90-Hz refresh rate) at a viewing distance of approximately 60 cm. All analyses were completed using JASP statistical software (JASP TEAM, 2019).

Visual task description and procedure. The methods are identical to the methods of Experiment 2 except as described below.

Memoranda. In the three-memory-item condition, four memoranda were presented at the beginning of each trial and were displayed for 750ms. An outline surrounded three of the four circles indicating that participants were supposed to only memorize those specific circles (see Figure 14). The outline always surrounded the upper two and bottom right circles, and participants were instructed to only memorize the outlined circles. In the four-memory-item condition, four memoranda were presented at the beginning of each trial and were displayed for 1000ms. An outline surrounded all of the circles indicating that participants were supposed to memorize all the circles. Importantly, stimuli consisted of different color filled circles, not containing a specific texture seen in Experiments 1 and 2.

Search. The search was identical to Experiment 2 except for the stimuli used. See Table 4. In the M1 distractor condition, the circle's color was the same as the memorized item appearing in the first (top left) position. In the M2 distractor condition, the circle's color was the same as the memorized item in the second (top right) position. In the M3 condition, the circle’s color was the same as the memorized item in the third (bottom right) position. In the M4 condition, the circle’s color was the same as the memorized item in the fourth (bottom left) position. In the new-distractor condition, the circle consisted of a color that was not part of the memoranda. In the no-distractor condition, all seven circles were gray.

Table 4.
Experiment 3 Distractor Types

Distractor Condition	Description
	Three-Item Memory Condition
M1 Distractor	Circle’s color is the same as the item presented on the top-left
M2 Distractor	Circle’s color is the same as the item presented on the top-right
M3 Distractor	Circle’s color is the same as the item presented on the bottom
Uncued Distractor	Circle’s color is the same as the uncued item
New Distractor	Circle’s color is different from the cued and uncued items
No Distractor	No circle with color is present
	Four-Item Memory Condition
M1 Distractor	Circle’s color is the same as the item presented on the top-left
M2 Distractor	Circle’s color is the same as the item presented on the top-right
M3 Distractor	Circle’s color is the same as the item presented on the bottom-left
M4 Distractor	Circle’s color is the same as the item presented on the bottom-right
New Distractor	Circle’s color is different from the cued and uncued items
No Distractor	No circle with color is present

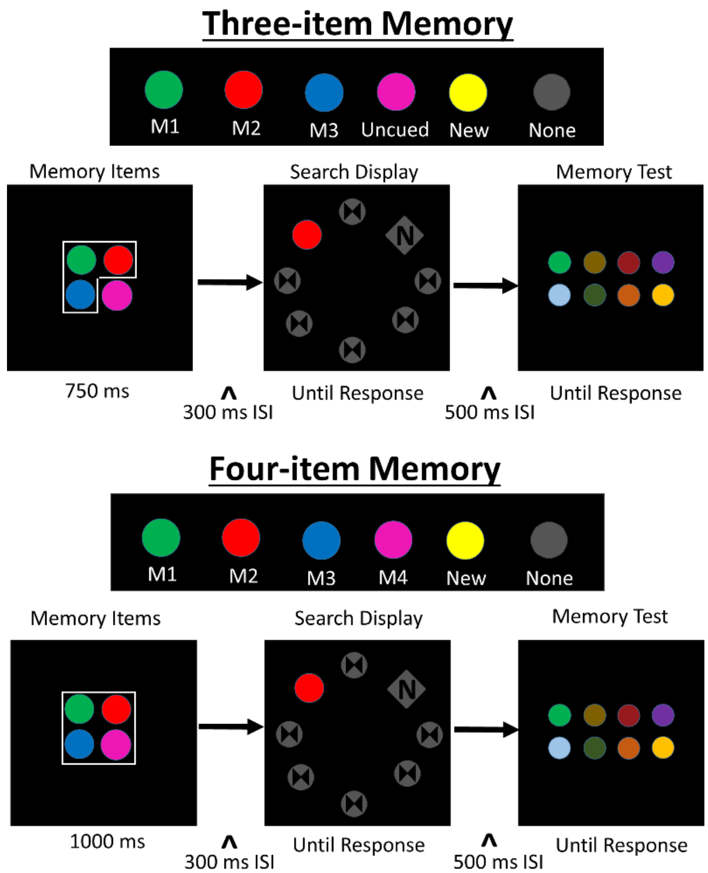

Figure 14. Trial display with six different possible distractor conditions per trial for the three-item memory, and four-item memory conditions (single feature).

Results. In the three-item memory condition, there was not a main effect of distractor condition, $F(5, 290) = 0.935$, $p = .459$, $\eta_p^2 = .02$. No RTs from the various distractor conditions were significantly different from one another, all $ps_{bonf} > .500$. See Figure 15.

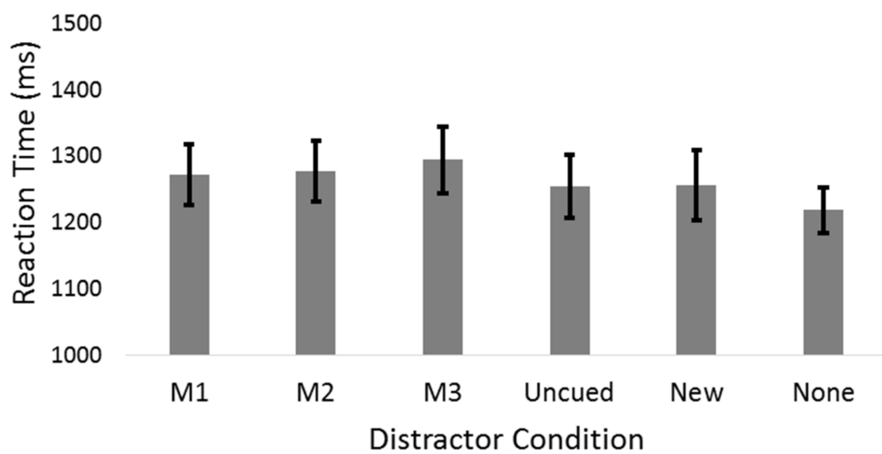

Figure 15. RTs for the search display as a function of distractor condition in the three-item memory condition. . Error bars represent standard errors of the mean.

In the four-item memory condition, there was not a main effect of distractor condition, $F(5, 290) = 0.982$, $p = 0.429$, $\eta_p^2 = .02$. No RTs from the various distractor conditions were significantly different from one another, all $ps_{bonf} > .500$. See Figure 16.

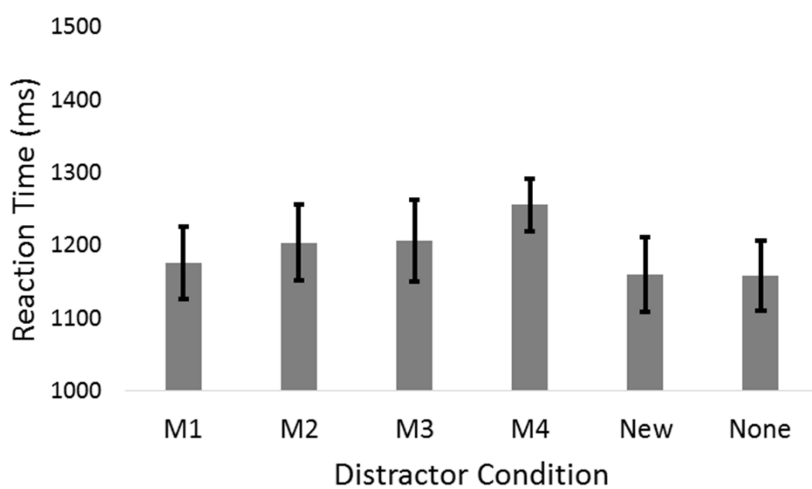

Figure 16. RTs for the search display as a function of distractor condition in the four-item memory condition.

A memory-capture index (MCI) was again calculated to measure the interference caused by distractors. An MCI value was calculated for M1, M2, M3, and M4 distractor conditions in the four-item memory condition. These values were summed to create a combined MCI effect. The same was done for the combined MCI effect in the three-item memory condition. That is, a separate MCI value was calculated for the M1, M2, and M3 distractor conditions and then these values were summed. The results of Experiment 3's MCI analysis do not suggest that all four representations were being maintained: the combined MCI effect of the M1, M2, M3, and M4 distractors in the four-item memory condition did not differ significantly from the combined MCI effect of the M1, M2, and M3 distractors in the three-item memory condition (Mean Difference = 0.59, $p = .58$).

Discussion. The results of Experiment 3 do not suggest that three single-featured visual working memory representations were being maintained during search. The three-item memory condition did not replicate the results found in Experiment 1. While the M1, M2, and M3 distractor conditions were not significantly different from one another, they were also not significantly different from the Uncued, New, or None conditions. The four-item memory condition had similar findings. The M1, M2, M3, and M4 conditions were not significantly longer from one another, nor were they significantly longer than the New and None conditions. Additionally, the MCI analysis does not suggest that all four representations were being maintained. The combined MCI effect of the M1, M2, M3, and M4 distractors in the four-item memory condition did not differ significantly from the combined MCI effect of the M1, M2, and M3 distractors in the three-item memory condition (Mean Difference = 0.59, $p = .58$).

These results suggest that participants were either not maintaining the cued items in memory or that the maintained items did not interfere with visual search. It may be that more complex items (i.e., dual-featured items) appear as more unique, compared to single-featured items, and thus are easier to maintain as a visual working memory representation during a simultaneous search. Other possible explanations are discussed in the General Discussion below.

General Discussion

The goal of the presented research was to further our understanding of the underlying components that influence our ability to conduct visual search, and its relationship with visual working memory. The series of studies was built off the results from the pilot replication of an experiment from Chen and Du (2017), suggesting that the capacity of visual working memory during visual search appears to be two items. I extended these findings to three additional experiments, and tested whether this capacity can extend to more than two items, and if the results change based on the number of features of visual working memory stimuli.

In Experiment 1, I investigated whether two items represent the full capacity of visual working memory during visual search, or if this could extend to three items in visual working memory that simultaneously controls attention during visual search. The results of Experiment 1 clearly suggested that not just two, but three representations were being maintained during visual search. The two-item memory condition replicated the results found in the pilot study, and the three-item memory condition extended these results, where the M1, M2, and M3 distractor conditions all had significantly longer RTs than the New and None conditions, while the M1, M2, and

M3 conditions were not significantly different from one another. These results supported the notion that there are multiple active slots in visual working memory, and that three visual working memory representations may be simultaneously activated to guide attention.

Experiment 2 aimed to replicate and extend these findings. Here, I investigated whether three items is the limit, or if the capacity can extend to four items in visual working memory that can simultaneously control attention during visual search. However, the results of Experiment 2 conflicted with the results of Experiment 1 by not supporting the hypothesis that three visual working memory representations were being maintained during search. Only the M1 distractor condition had significantly longer RTs than the New and None conditions. The four-item memory condition had mixed results as well. Only the M1, M3, and M4 conditions were significantly longer than the None condition, and the M4 condition was the sole condition significantly longer than the New condition.

Experiment 2's results suggest one of three possibilities. One possibility is that the capacity of visual working memory during visual search is two. That is, Chen and Du's (2017) findings, my pilot study's positive replication of Chen and Du's study, and the positive replication of my pilot study's finding in my Experiment 1's two-item condition, all support the hypothesis that two items held in visual working memory can simultaneously guide attention. If the capacity of visual working memory during visual search is two, this suggests that the null result of my Experiment 2 three-item condition is correct and the positive result of my Experiment 1, three-item condition was due to Type I error.

The second possibility is that the capacity of visual working memory during visual search is three. In this case, the result of my Experiment 2's three-item condition was either the result of a Type II error, or the additional uncued item in the display was encoded and maintained such that participants were attempting and failing to maintain four items in visual working memory. In Experiment 1 and the pilot, the results suggested that participants were not maintaining the uncued item. However, in Experiment 2, there is no evidence to suggest that participants were not maintaining this item. If they were maintaining the uncued item in Experiment 2, but did not in the previous studies, this could be due to the difference in configurations or due to the total number of stimuli presented. That is, it is possible that with smaller numbers of stimuli, there is leftover visual working memory capacity to direct attention away from irrelevant stimuli so they are not captured, whereas if the capacity is three with four stimuli (one uncued), there is no remaining capacity to direct attention away from the irrelevant stimulus, and so it is also captured. In this case, the four captured stimuli exceeded capacity, such that the memoranda were not maintained.

Based on the results from Experiment 2, I hypothesized that there may be a trade-off between the complexity of items and the total number of items that can be stored in visual working memory at a given time (Alvarez & Cavanagh, 2004). The stimuli used in the previous experiments consisted of items that have dual features (i.e., color and texture). To follow up Experiment 2, Experiment 3 investigated whether three items, using single feature stimuli (color only, no textures) is the capacity of visual working memory during visual search, or if the capacity can extend to four items with a single feature. The results of Experiment 3 suggested that neither three nor four single-featured visual working memory representations could be maintained during search. In the three-item memory condition, the M1, M2, and M3 distractor conditions were not significantly different from one another. However, they were also not significantly different from the Uncued, New, and None conditions. The four-item memory condition had similar non-significant findings. The M1, M2, M3, and M4 conditions were not significantly different from one another, nor were they significantly different than the New and None conditions. These results suggested that even when items are simplified to a single feature, the capacity appears to be capped at two or three representations that can be simultaneously activated during search to guide attention.

A number of studies suggest that the number of features is irrelevant for maintenance. Luck and Vogel (1997) demonstrated that visual short-term memory capacity for objects containing a single feature was equivalent to capacity for certain types of multi-featured objects. They argued that visual short-term memory capacity is determined by the number of integrated objects rather than by the number of individual features (see also Vogel, Woodman, & Luck, 2001). Likewise, Awh, Barton, and Vogel (2007) asked whether the capacity of visual working memory depended on the number of items, or if capacity is reduced as item complexity increases. They found that capacity estimates for even the most complex objects were equivalent to the estimate for the simplest objects, suggesting that visual working memory represents a fixed capacity for number of items, regardless of complexity. Specifically, they concluded that visual working memory stores three to four objects regardless of their complexity during the retention interval. These studies support the integrated item view of visual working memory, which argues that items (rather than features) affect visual working memory capacity, so that adding an extra feature to an item does not result in any extra cost to working memory capacity (Luria & Vogel, 2011).

Based on the results of the experiments, it appears that the storage of complex items (dual featured) were able to influence visual search more so than the storage of simple, single-featured items. This finding was unexpected, but I offer some speculation as to why this pattern of results might have occurred beyond the possibility of Type 1 and Type II errors.

One possibility is that the more complex stimuli were better encoded and were thus more active in visual working memory than the single-featured stimuli, increasing their bias on attention. This would be in line with research from long-term memory suggesting that items containing multiple features and increased complexity might improve encoding and thus subsequent maintenance and retrieval (Bradshaw & Anderson, 1982). Specifically, Bradshaw and Anderson (1982) found that complex, highly elaborate memories were better recalled than simpler, less elaborate memories. This is done by using elaborative encoding strategies. Elaborative encoding refers to the process of relating to-be-remembered information to other information that is pertinent to the target information (Ellis, Thomas, & Rodriguez, 1984). Those that create the more complex and elaborate memory-information strategies, remember more items in long-term memory. We see these strategies used in memory experts, such as mnemonists, who are able to recall unusually long lists of data, such as unfamiliar names, lists of numbers, entries in books, etc. (Luriia, 1987). Likewise, synesthetes can have superior memories because they encode memoranda with additional features. Smilek, Dixon, Cudahy, and Merikle (2002) describe a case study in which an individual experiences synesthetic colors (i.e., photisms) when she sees, hears, or thinks of digits. This added layer of complexity allows people with synesthesia to have superior memories (Radvansky, Gibson, & McNerney, 2011). It may be that the more complex, elaborate items in Experiment 2 were easier to hold in memory during a concurrent visual search task. However, there is little reason to believe that long-term elaborative encoding processes parallel working memory encoding processes. Further, if this were occurring, then memory accuracy for the complex, two-feature memoranda should be higher than for the simpler single-feature memoranda. This was not the case: The memory test accuracy proportions for the memory of 3 and 4 in Experiment 2 were .78 (*SD* = .04) and .77 (*SD* = .05), respectively, whereas the memory test accuracy for the memory of 3 and 4 conditions in Experiment 3 are .84 (*SD* = .06) and .80 (*SD* = .08), respectively.

Another possibility I considered was that single-featured items were more confusable than more unique, dual-featured items. This would be in line with research from short-term memory demonstrating that lists of similar-sounding words are more confusable and therefore harder to recall than lists of dissimilar-sounding words (Baddeley, 1966). The phonological similarity effect has been shown in working memory models as well (Tehan, Hendry, & Kocinski, 2001). While the possibility of a visual parallel to the phonological similarity effect might be more likely than the previous possibility discussed, this were occurring, then once again, memory accuracy for the complex, two-feature memoranda should have been higher than for the simpler single-feature memoranda. This was not the case.

These results may also be explained by the findings of Treisman and Gelade (1980). In their theory of search, it is theorized that people can find single-featured items without effortful search. Search for items with one feature does not require attention. However, items with a conjunction of features require effortful attention, and must be searched to be found. This may be why there were no significant differences between any distractor condition in Experiment 4, whereas I do find effects in Experiments 1 and 2. That is, the appearance of distractor items during search did not and could not guide participant's attention because they were single-featured items.

A final possible explanation for the difference in results from Experiment 2 and 3, is that the single feature items in Experiment 3 may have been verbalizable by participants. By mentally verbalizing and rehearsing the memoranda during the search task, it is likely that participants' attention would not be pulled by the presence of a visual distractor, or at least not as much if they were holding visual representations in visual working memory instead (as they appear to be in Experiments 1 and 2 where the possibility of the two-featured stimuli being verbalizable is low). If this is the case, then visual distractors would not disrupt verbal rehearsal and visual distractors may not bias attention. This may be why I found no significant differences between any of the distractor conditions in both of the memory conditions in Experiment 3. Further, if participants are not being distracted during visual search while mentally rehearsing colors, than I should also find that RTs in Experiment 3 are faster overall than RTs in Experiment 2. Indeed, this is the case. The mean RT across conditions in Experiment 2 is 1.32, whereas the mean RT across conditions in Experiment 3 is 1.23. In addition, if participants are able to mentally rehearse color names in Experiment 3, one would expect to find higher memory accuracy scores compared to Experiment 2. I find this as well (see Appendix, Table 1). The memory test accuracy proportions for the memory of 3 and 4 conditions in Experiment 2 are .78 (*SD* = .04) and .77 (*SD* = .05), respectively, whereas the memory test accuracy for the memory of 3 and 4 conditions in Experiment 3 are .84 (*SD* = .06) and .80 (*SD* = .08), respectively.

It is also important to note the way my research question was asked, and how I attempted to answer this question. Before beginning this research, I asked, “How many items can we store in visual working memory while simultaneously conducting a visual search?” The experimental design used in each experiment recorded responses from participants in two ways: Their reaction times during visual search under different distractor conditions, and their accuracy for items in visual working memory. I decided to assess the research question based on how items in visual working memory influenced attention, or how distractors that consisted of items in visual working memory slowed visual search. If instead I had focused on the number of items in visual working memory recalled, I would have designed a different experiment which may have led me to draw different conclusions.

Conclusion

Across a pilot study and three experiments, I demonstrated that multiple items held in visual working memory can capture attention and interfere with visual search. In the pilot experiment, I replicated Chen and Du’s (2017) experiment demonstrating that not one, but two items held in visual working memory can capture attention. In the first experiment, I demonstrate that not two, but three items held in visual working memory can capture attention. In the second and third experiments, the results suggested the capacity may be capped at two or three representations that can be simultaneously activated during search to guide attention, and that simplifying memoranda to a single feature does not increase capacity. These findings are in contrast to earlier research claiming that only one visual working memory representation can influence attention directly at a time during visual search (Olivers et al., 2011; van Moorselaar et al., 2014; Woodman & Luck, 2007).

The stimuli were designed such that the memoranda were selected from multiple possible stimuli, and that the stimuli varied trial to trial. This design means it is unlikely participants committed the memoranda to long-term memory. Further, the results do not support the argument that the memoranda are simply being alternatively activated to influence visual search, such that multiple items are sharing the same slot available for an active memory item. Instead, the results suggest that at least two, and possibly three representations can be simultaneously activated in visual working memory.

The presented research addresses cognitive factors that underlie behaviors and problems faced by people every day in life. Searching for an item in a crowded visual environment can be a routine and irritating task for the average person, such as searching for your car keys, or looking for a friend at a baseball game. Importantly, conducting a difficult visual search can also be a high stakes task, where careers and sometimes lives are at stake. Air traffic controllers must be highly attentive in their radar searches to ensure the safe flow of air traffic, and avoid potential catastrophic accidents. Radiologists visually search X-rays for diseases and injuries, where a misdiagnosis or failure to find a tumor can potentially lead to loss of life.

Visual search is a complex task that is influenced by visual working memory. Visual working memory does not appear to reflect as severe a bottleneck in information processing as previously thought. Rather than a single active visual working memory representation biasing attention during concurrent visual search, I provided evidence that two and possibly three visual working memory representations can simultaneously capture attention during concurrent visual search. Thus, our capacity to hold multiple items in mind while searching is higher than previously thought, as is the likelihood of those memoranda interfering with our search.

Appendix

Table 1
Accuracy Results for Visual Search and Memory Test Across Experiments

Experiment	Condition	Mean Visual Search Accuracy (SD)	Mean Memory Test Accuracy (SD)
Pilot	Memory = 1	.97 (.03)	.76 (.09)
	Memory = 2	.96 (.03)	.74 (.08)
Experiment 1	Memory = 2	.92 (.10)	.81 (.12)
	Memory = 3	.90 (.12)	.76 (.09)
Experiment 2	Memory = 3	.97 (.02)	.78 (.04)
	Memory = 4	.96 (.03)	.77 (.05)
Experiment 3	Memory = 3	.96 (.05)	.84 (.06)
	Memory = 4	.92 (.08)	.80 (.08)

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