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Visual working memory load plays limited, to no role in encoding distractor objects during visual search

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ABSTRACT

Previous research raised the counterintuitive hypothesis that searching for multiple potential targets leads to *increased* incidental encoding of distractors. Are these previously reported findings due to increased visual working memory (VWM) engagement, or less precise target templates? In four experiments, we examined the effect of VWM load during visual search on incidental encoding of distractors. Consecutive target repetitions indirectly reduce template-related VWM demands but failed to reduce recognition for distractors relative to conditions where the targets were novel. Distractors that were subsequently recognized attracted longer cumulative dwell time, regardless of search condition. When placed in a dual-task situation where search was performed while holding a working memory load, recognition for distractors was marginally improved relative to a search task without additional VWM demands. We ruled out the possibility that the dual-task was not sufficiently difficult to trigger the scrutiny of distractors required for significant encoding benefits by showing a decrement to encoding when search time was limited. This suggests that widening the attentional set is the crucial factor in improved incidental encoding given that observers can assign differential status to various contents of VWM. Thus, utilizing VWM resources in general appears insufficient to meaningfully improve incidental memory.

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Incidental encoding; visual search; visual working memory; target template; eye tracking

Visualize a package of bowtie pasta. You might be surprised to find your memory matches well with a popular brand in your local market despite never having bought or opened a package. These types of visual traces in our memory, established without deliberate encoding, are called incidental memories. Did the bowtie memory form during the many occasions you passed by bowtie pasta while searching for spaghetti, or is the memory more likely to have formed on grocery trips where your search was not as clearly defined? Prior visual search research has already revealed our capacity to incidentally form visual memories of non-target items: distractors in the visual search literature, bowtie pasta in the example above (Castelhano & Henderson, 2005; Thomas & Williams, 2014; Williams, 2010a, 2010b; Williams et al., 2005). Incidental memories give clues as to the internal processes and stimulus properties that guide visual search by indicating what in the search environment was or was not attended or processed.

They also shed light on the mechanisms of encoding visual memories, such as the dependency of encoding on the target, type of search, or the benefit to encoding of finding an image versus just seeing it (e.g., Thomas & Williams, 2014). But what types of search enhance or inhibit this capacity to unintentionally familiarize one's self with their surroundings?

A handful of prior studies (Guevara Pinto & Papesch, 2019; Guevara Pinto et al., 2020; Hout & Goldinger, 2010, 2012) have suggested a larger VWM load facilitates the formation of incidental memories of distractors during visual search and rapid serial visual presentation (RSVP). Loading VWM in this manner has been hypothesized to enhance encoding of distractors (Hout & Goldinger, 2010) through impairing observers' ability to filter out irrelevant information (see Conway et al., 2001). Each experiment has manipulated VWM load with the same technique – varying the number of cued potential search targets from between one and four, thereby placing

participants under higher VWM load as the number of potential targets increases. Each experiment has replicated the finding that participants recognize a greater proportion of distractors that appeared while the number of potential search targets was greater. This well-established phenomenon defies our intuitions, given that encoding of visual details seems to take deliberate attention and focus. Maintaining three or four targets in mind engages VWM resources at or beyond almost everyone's capacity (see Balaban et al., 2019), so it is not at all obvious whether there are resources to spare to facilitate memorization of distractor details under these circumstances.

Consider, for example, the ubiquitous technique for learning human anatomy via excruciatingly detailed colouring in workbooks. Prior research suggests that search for one of many organs (the spleen, gall bladder or appendix) might facilitate memory for other organs that are incidentally encoded while engaged in this task. The primary proposed mechanism for the hypothesized benefit in this situation is increased VWM engagement when searching for more than one target. The primary goal of the current paper is to better understand this set of surprising findings by exploring whether the observed benefits associated with multiple target search are driven by the increase in VWM demands associated with multiple-target search. The current study addressed this research question in four experiments, each implementing a method for VWM manipulation whose influence on distractor encoding was heretofore unknown.

As the number of search targets increases, search performance will be affected by other factors in addition to VWM load. There is evidence that at least two of these factors are related to incidental distractor encoding, namely target-distractor similarity and the utility of the search template for guidance and verification (template effectiveness, for short). That these factors vary in proportion with the number of search targets, and hence VWM load, motivated us to explore the influence of VWM load on distractor encoding using manipulations that do not confound VWM with these factors. The researchers investigating incidental distractor encoding under variable numbers of targets have themselves acknowledged the potential influence of these factors (Guevara Pinto & Papesh, 2019; Guevara Pinto et al., 2020; Hout & Goldinger, 2010). Below,

we review the literature demonstrating a relationship of these factors to incidental distractor encoding and potential cognitive and search behaviour mechanisms therein. Next, we describe the basic VWM manipulation used in our first two experiments, considering factors that may vary alongside VWM load.

Influences on distractor encoding

The method of target cueing used by Hout and Goldinger (2010, 2012), Guevara Pinto and Papesh (2019), and Guevara Pinto et al. (2020) is integral to the assertion that searching for multiple targets increases VWM load. Participants were shown veridical previews of the targets and these targets changed on every trial. All stimuli were photographs of a broad variety of items (Brady et al., 2008). Thus, in order to determine whether targets were present or absent (as the task demanded in some experiments) or where the target was located (in other experiments), participants presumably maintained an active internal representation of the targets in VWM rather than long term memory (LTM) because the images were likely novel to participants even if they depicted familiar objects. Indeed, there is strong electrophysiological evidence that increasing the number of targets increases the ongoing neural activity strongly associated with VWM resources. Carlisle et al. (2011) found that the amplitude of the contralateral delay activity (CDA), an event-related potential (ERP) strongly associated with VWM (Luria et al., 2016), doubled when participants were asked to prepare to search for two, rather than one potential targets. This appears to be a neural index of *target templates*, which are thought to selectively represent features to allow the observer to discriminate the target from its expected context (Bravo & Farid, 2016; Schmidt & Zelinsky, 2017). Target templates help determine where to look (i.e., "guidance") and enable decisions regarding whether the target has been found (i.e., "verification"; Hout & Goldinger, 2015; Malcolm & Henderson, 2009). Prior research on target-distractor resemblance and template effectiveness have used similar designs, allowing us to evaluate the importance of those factors in distractor encoding under variable numbers of potential targets.

Incidental memory is better for distractors bearing more visual similarity to search targets (e.g., shared

colour or category) than those bearing less similarity (Thomas & Williams, 2014; Williams, 2010a, 2010b; Williams et al., 2005). This is likely a consequence of the tendency for distractors that most closely resemble the template on a given trial to be most likely to draw attention (Becker, 2011; see Alexander & Zelinsky, 2011, 2012). If multiple targets are cued it is likely that more distractors would draw attention than if a single target is cued because this increases the opportunity for target-distractor resemblance for at least one of the targets. Crucially, this depends on targets and distractors being sampled randomly from a stimulus pool such that there is a roughly equal probability of any potential target resembling a distractor. If, however, targets or distractors were all selected from separate categories (e.g., all targets are clocks and all distractors animals) then is it less likely that adding potential targets would increase changes of target-distractor resemblance. Hout and Goldinger (2010, 2012) and Guevara Pinto and Papesh (2019) stated no constraints on the selection of stimuli. We can infer that participants searching for more potential targets observed a greater likelihood or degree of target-distractor resemblance, contributing to their gains in later distractor recognition. This is consistent with Cunningham and Wolfe's (2014) model of hybrid search where participants engaged in a search for one of many targets within a category are able to quickly ignore potential targets that bear little resemblance to the target set (e.g., alphanumeric items if searching for animals), and items that are similar the target set (e.g., other animals if searching a target set of animals) are processed much more deeply.

Guevara Pinto et al. (2020) specifically tested and supported the hypothesis of boosted distractor recognition via template ineffectiveness proposed in Hout and Goldinger (2010, p. 1275): search for multiple potential targets amongst distractors, compared to one target, "required people to make more frequent and careful mental comparisons, pitting each distractor against three potential targets with distinct visual details." The evidence that such detailed comparison processes occurred to a greater extent as the potential target number increased is that when participants failed to select the correct image in a 16 alternative-forced-choice (AFC) recognition test of distractors, they were more likely to select foil images possessing greater empirically-derived

resemblance to the distractor when they had seen that distractor while searching for more potential targets (Guevara Pinto et al., 2020). In other words, difficult search required participants to scrutinize the distractors and, as a result, when they failed to select the distractors from a lineup of within-category foils they tended to choose an object bearing high resemblance. Note, this is consistent with the influence of target-distractor resemblance on distractor encoding. Besides multiple cues, inaccurate or imprecise cues (e.g., "vehicle") impair accuracy and aid incidental distractor encoding compared to pictorially accurate cues (e.g., a picture of the exact target police car) in RSVP (Guevara Pinto & Papesh, 2019). A wealth of research into the effectiveness of the target template provides a fairly detailed account of how search for multiple targets suffers in accuracy and efficiency.

Templates that better match the visual details of the target-to-be-found allow faster visual search, while less specific or less accurate templates slow down visual search (Bravo & Farid, 2009, 2012; Hout & Goldinger, 2015; Malcolm & Henderson, 2009; Menneer et al., 2009; Schmidt & Zelinsky, 2009). Specific changes to eye movements underlie these effects. More veridical target cues reduce fixations in areas that do not contain the target and allow faster identification of targets and non-targets once gaze is directed on them (Hout & Goldinger, 2015; Malcolm & Henderson, 2009). When observers are cued with multiple potential targets, requiring retention of multiple templates in VWM, observers search more areas and take longer to positively verify the target from the time their gaze first lands on it (Hout & Goldinger, 2015). As perceptual dissimilarity between the cued targets increases, search spreads even further and target verification slows down, leading to overall greater reaction times (Hout & Goldinger, 2015). Similar results emerge when there is only a single potential target but the cue deviates from an exact perceptual match of the target-to-be-found (Malcolm & Henderson, 2009; Schmidt & Zelinsky, 2009), such as when merely a verbal label (e.g., "water glass") or a pictorial cue from the same category is displayed to the observer. Multiple cues or imprecise cues (compared to single, veridical cues) in RSVP appear to reduce the size of the spatial attentional window, reducing observers' ability to detect peripheral stimuli simultaneous with the search

stream (Guevara Pinto & Papesh, 2019). In considering the foregoing evidence, the multiple target conditions of Hout and Goldinger (2010, 2012), Guevara Pinto and Papesh (2019), and Guevara Pinto et al. (2020) likely interfered with the well-guided search from the single-target condition, leading observers to examine more distractors for longer durations and in more detail.

Research on incidental encoding and recognition consistently finds that time spent fixating each separate distractor image over the course of visual search trials differs depending on whether a particular image was remembered or forgotten (Hout & Goldinger, 2012; Williams, 2010b; Williams et al., 2005). However, factors beyond eye movements also predict encoding of images and objects more generally (not just distractors). The type of task (search versus memorization) alters the relationship between dwell time and distractor encoding (Helbing et al., 2020). Curiously, under some circumstances, search targets can be better encoded despite shorter dwell times than distractors (Thomas & Williams, 2014). In addition, the fact that search for more than one target in RSVP search boosts incidental encoding (Guevara Pinto & Papesh, 2019; Guevara Pinto et al., 2020; Hout & Goldinger, 2010) suggests the putative benefit of VWM on distractor encoding may not require longer dwell times for recognized images. Therefore, in addition to behavioural analyses of visual search and incidental recognition (described below), we tested the interaction of subsequent memory effects on dwell time with VWM load during search in Experiments 1 and 2.

An alternative VWM manipulation to multiple targets

While it has been duly acknowledged and demonstrated that factors in addition to VWM load contribute to improved incidental distractor encoding during search for multiple targets, it is an open question whether other methods of VWM manipulation can alter such encoding. For such an alternative we may look to a burgeoning electrophysiological literature that suggests repeatedly searching for the same cued target on consecutive trials reduces template-related VWM demands (Drew et al., 2018; Gunseli et al., 2014; Reinhart et al., 2016; Schneider et al., 2018; Servant et al., 2018; Woodman et al., 2013).

After briefly describing this literature, we will argue that manipulating target novelty via repeated consecutive search for a single target has an added benefit of minimizing the influence of target-distractor resemblance, although it may not solve the problem of separating VWM load from template effectiveness.

In ERP studies cited above involving repeated search, the CDA was measured in an interval after a preview of the target but before the search array appears. The CDA indicates with high fidelity the number of elements held in VWM (Feldmann-Wüsterfeld et al., 2018), individuals' VWM capacities (see Luria et al., 2016 for a meta-analysis), and may reflect the level of detail of the template in relation to the anticipated perceptual difficulty of the upcoming search (Schmidt & Zelinsky, 2017). The CDA amplitude during the retention interval between target cue and search initiation steadily decreases as the number of previous encounters with a target increases. The first encounter with a target evokes the largest CDA. With further repetition, the CDA declines asymptotically until it is no longer significantly different from zero (Carlisle et al., 2011, Experiment 2). Thus, we infer that to retain a template of a new target participants recruit greater VWM resources than when retaining a template of a target that has been encountered on directly preceding trials.

While VWM demands decline with increasing target familiarity, both accuracy and speed of visual search increase. Servant et al. (2018) account for this performance gain by suggesting that control of search behaviour transfers from ongoing representation in VWM to more passive representation when stored in LTM. Repeated searches for the same target lead to more automatic detection of the target via long-term memory mechanisms, as indicated by reduced FN400 amplitudes (Drew et al., 2018; Servant et al., 2018). The asymptotic decay of the CDA, FN400, and reaction times supports this theory. Another facilitatory factor may be increased salience of target features, perhaps through priming, as indicated by increased N2pc amplitudes on consecutive searches for the same target (Drew et al., 2018; Eimer et al., 2010; Hickey et al., 2011).

In Experiments 1 and 2, we manipulate target novelty within and between subjects, respectively. Both experiments cued the target exactly as it would appear in the search array. In the former

experiment, different distractors appeared at specific phases within target repetition cycles. We hypothesize that in earlier compared to later target encounters distractor encoding will benefit because template-related VWM load is higher. In Experiment 2, we compared distractor encoding between participants who searched for new targets on every trial (Novel group) and those who searched for a single target for the entirety of the experiment (Repeat group). The former participants should demonstrate greater recognition for distractors because VWM demands for novel target search are greater. Importantly, in contrast to prior work where having more targets necessarily increases the amount of target-distractor similarity, this design ensures that target-distractor similarity is equated across our different conditions.

Notably, whether repeated search increases the precision of the template or whether it transfers, unchanged, from VWM to LTM is not clear. Preparatory activity involved in template maintenance becomes less important if the template has been committed to LTM (Drew et al., 2018; Servant et al., 2018) and neural responses to target features become sensitized through intertrial priming (e.g., Eimer et al., 2010; Hickey et al., 2011). Despite providing an exact target preview before each search, it may nevertheless be the case that templates become more precise with repeated search. Thus, similar to multiple- versus single-target search, VWM load could be confounded with template quality in repeated search. We will address this concern by more directly manipulating VWM load in Experiments 3 and 4.

Experiment 1: 10× target repetition

Method

In a within-subjects design, we assessed participants' incidental encoding of distractors while participants searched for a target on 10 consecutive trials. Separate groups of distractors appeared at different phases of target repetition. This allowed us to test the hypothesis that under conditions of higher VWM load (i.e., when participants were newly introduced to the target) incidental encoding of distractors should be higher than under conditions of lower VWM load during search (i.e., after participants already had consecutively searched for the target

multiple times). We also tracked participants' eyes during visual search to see whether cumulative dwell time on distractors would mediate this effect. To give stable measures of visual search performance, dwell time on distractors, and distractor recognition, we separated the phases of target repetitions one through three, four through seven, and eight through 10 into "early," "middle," and "late" stages. VWM load during search should have been relatively high, moderate, and low, in each respective stage.

Participants

Thirty-two participants completed Experiment 1, with a mean age of 20.8 years \pm 2.8 (mean \pm standard deviation; 8 males). Four additional participants were consented for Experiment 1 but were not analyzed because of head motion or failure to calibrate the eye tracker.

Design

Experiment 1 consisted of 400 visual search trials followed by 80 trials of a surprise memory test for all the distractors viewed through the course of the visual search task (see Figure 1). At the beginning of each visual search trial, the target image was presented on the screen. After participants pressed the spacebar to initiate visual search, there was a blank screen for a duration between 500 and 700 ms. The search array consisted of eight images and contained the target image half the time. On target-absent trials, all eight images were drawn from a subset of 80 distractors. On target-present trials, a single distractor was replaced by the target. The search array was visible until participants responded with the keyboard to indicate whether the target was present or absent. Feedback was displayed immediately after each trial for 638 ms. This was followed by a blank screen for 500 ms until the beginning of the next trial.

The stimuli were photographs of real-world objects (Brady et al., 2008). 100 stimuli were randomly selected to serve as potential distractors, whereas the remaining 1894 images were used as potential practice images, targets, and foils for the memory test. Practice images, targets, and foils were randomly sampled without replacement from this larger pool for each participant. 80 distractors were randomly sampled from the separate pool for each participant.

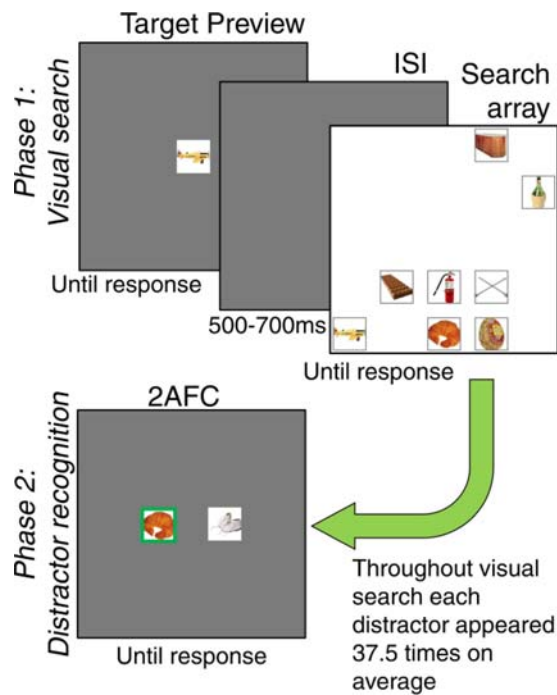


Figure 1. Visual search and surprise recognition layout. Proportions altered to show detail. Not shown are frames for feedback or onscreen response instructions. The same applies to Figure 6. Recognition of each distractor that appeared during visual search was tested in a 2AFC design. The green frame indicating correct response was not visible to participants.

Only 40 unique targets were used for experimental trials, and the target changed every 10 trials. Over the course of the visual search trials all 80 distractors were displayed on average 37.5 times – some more, some less, depending on which distractors were randomly replaced by the target on target-present trials. The 80 distractors were grouped randomly per participant into 10 sets of eight images each. Each set was repeatedly used every 10 visual search trials. For example, distractor set 1 was used on trial 1, 11, 21, and so on. In Experiment 1 this allowed us to separately compare the memory for distractors viewed during early repetitions of the visual search target (repetitions 1–3), middle repetitions (4–7), and late repetitions (8–10).

The incidental memory test consisted of 80 2-alternative forced choice (2AFC) trials (Figure 1). On each trial, two images were displayed next to each other, one of which was a distractor previously presented during visual search, the other was an image that had not been presented before. Participants responded with the keyboard to indicate whether the object they recognized was on the left or the right side. After the response, the images remained

on screen for an additional 400 ms until the next trial began. Feedback about the accuracy of the response appeared 250 ms after response and lasted 150 ms.

Procedure

Participants completed the study either for credit in psychology courses or for monetary reward of \$10 per hour. All but two participants in the reported analyses met the following inclusion criteria: age between 18 and 40 years; normal or corrected to normal vision, and; full colour vision. In Experiment 1 one participant was colourblind, and in Experiment 2 one participant was 51 years old. Data from neither participant markedly differed from the rest of their respective sample. With few exceptions the experiment lasted for less than one hour. All participants provided written informed consent. The procedures were approved by the IRB at the University of Utah.

Participants were instructed that the experiment was part of a study on visual search. No mention was made of the memory test at the end of the experiment. Participants completed 12 practice trials before beginning the 400 experimental trials. They were encouraged to respond quickly and accurately using the “F” key to indicate the target was present and the “J” key to indicate it was absent, using their left and right index fingers respectively. After participants completed the 400 visual search trials the experimenter told them that there was one final task that had not been mentioned previously. Upon completion of the experiment participants were debriefed. Participants completed the study one at a time in a dimly lit room to accommodate eye tracking (details below).

Apparatus

The Psychophysics Toolbox (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997) for MATLAB was used to present all stimuli and record responses.

Stimuli were presented on an LCD computer monitor at 1920 by 1080 resolution. Viewing distance was 65 cm. A central white square measuring 24.6° of visual angle served as the background for the search array, while the rest of the screen was dark grey. Stimuli were randomly placed with their centres on an invisible square grid that had 5 possible positions both side-to-side and up and down. The space

between these locations measured 3.5° so that the spaces between edges of images subtended 1.0° . To separate the stimuli from the background a thin grey frame was placed around each image.

Eye tracking. During visual search participants' eyes were tracked with the EyeLink Plus (SR Research, Ontario, Canada) with a sample rate of 1000 Hz. Participants kept their heads motionless with a chinrest. The eye tracker was calibrated at least twice during the experiment using a nine-point procedure. The first calibration was at the beginning of the experiment, the second was after the participant completed 200 visual search trials. Optionally, the experimenter could recalibrate every 50 trials. Identities and locations of images in the search array were co-registered with the eye tracking system to allow analyses of interest areas, such as cumulative dwell time on separate distractors. Cumulative dwell time was calculated as the summation of all fixations on a particular distractor throughout the course of all visual search trials. Gaze coordinate samples were categorized as fixations and saccades using the default settings in EyeLink Data Viewer (SR Research, Ontario, Canada).

Analysis

We analyzed visual search performance from target-present and -absent trials combined. We compared visual search RT and accuracy across the factor we expected to affect VWM load during search – target repetition stage. We expected to replicate findings that higher VWM load increases search RTs (Guevara Pinto & Papesch, 2019; Hout & Goldinger, 2010, 2012; Woodman et al., 2007) and error rates (Guevara Pinto & Papesch, 2019; Guevara Pinto et al., 2020; Hout & Goldinger, 2010, 2012). Accuracy on the surprise recognition test was submitted to the same analyses to determine the influence of VWM load during search on incidental distractor encoding. Different numbers of distractors appeared during the different conditions of visual search (24, 32, and 24 in the “early,” “middle,” and “late” stages) because the 10 trials in each repetition cycle could not be evenly divided. Accuracy was computed as the percentage of recognized distractors relative to the total number of distractors for a particular condition.

We assessed cumulative dwell time on distractors during visual search in the same manner as for RT and accuracy. We additionally compared cumulative

dwell time on distractors depending on whether they were subsequently recognized or forgotten, and crossed this subsequent memory factor with the VWM load factor. We expected that recognized distractors would be dwelled upon longer than forgotten ones and that more difficult search conditions would increase dwell times following Hout and Goldinger (2012), but had no specific predictions regarding the interaction of these effects.

Power calculations were performed based on effect sizes of number of search targets on incidental distractor encoding reported by Hout and Goldinger (2010, 2012), excluding the RSVP experiments in Hout and Goldinger (2010). Effect sizes were converted from η_p^2 to Cohen's f (Cohen, 2013, p. 284), and from f to Cohen's d using equations appropriate for the pattern of dispersion of group means for three or more groups (Cohen, 2013, pp. 276–280). The smallest calculated d comes from Hout and Goldinger (2010) Experiment 1, $d = 1.03$ and $\eta_p^2 = 0.21$. Experiment 1 exceeded 99% power for a dependent samples t -test with a sample size of 32. Power calculations were performed with GPower version 3.1.9.2 (Faul et al., 2007).

We report Bayes Factors (BFs) for tests that fail to reject the null hypothesis. In some cases, null results were followed up by pairwise t -tests, wherein we report the BFs for the follow-ups only. BFs were calculated with JASP software (JASP Team, 2020) using default settings. The BF indicates the goodness of fit of the observed data to the alternative hypothesis relative to the null hypothesis, such that a value of 3 or 0.33 indicates three times as much evidence in support of the alternative or the null hypothesis, respectively. Following the conventions of Jeffreys (2020), we consider BF values between 0.33 and 3 to indicate that the data does not strongly support either the alternative or the null hypothesis.

When the assumption of sphericity was violated the Huynh-Feldt correction was applied.

Results

Visual search

Reaction times were compared across early, middle, and late target repetitions, corresponding to repetitions 1–3, 4–7, and 8–10, respectively, using a repeated measures ANOVA (Figure 2). The significant

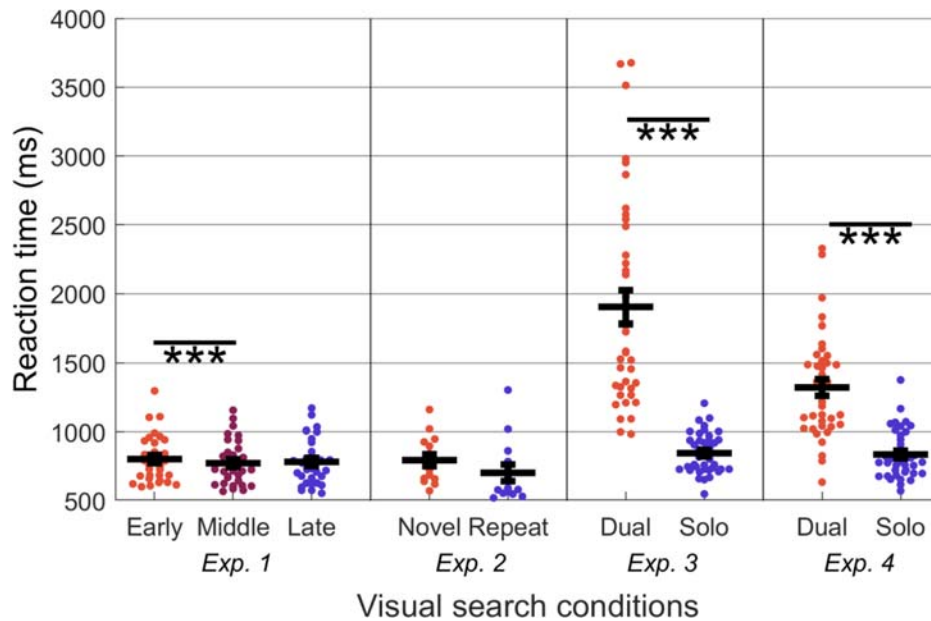


Figure 2. Visual search reaction time as a function of conditions across Experiments 1-4. Each dot represents the average RT for a single participant in a particular experimental condition. In Experiments 1, 3 and 4, each participant has multiple dots – one of each colour for each experimental condition. In Experiment 2, each participant has a single dot (blue or red) because the manipulation was between subjects. The large black marker represents the mean of each distribution. Error bars depict the mean \pm one SEM. Comparison lines indicate significance of pair-wise tests. *** $p < 0.001$.

effect, $F(1.48, 45.7) = 6.80$, $p < 0.01$, $\eta_p^2 = 0.18$, was driven by faster reaction times in middle compared to early ($M = 772$ ms \pm 160, 802 ms \pm 170) repetitions, $t(31) = 3.85$, $p < 0.001$, $d = 0.68$. However, this repetition-related speeding of RT was no longer significant for the late repetitions (782 ms \pm 168) compared to early repetitions, $t(31) = 1.94$, $p = 0.06$, $d = 0.34$, $BF = 0.99$.

Accuracy of visual search (Figure 3) was submitted to the same analyses as reaction time. The repeated measures ANOVA did not reveal a significant effect of repetition (early, middle, or late), $F(1.72, 53.4) = 1.27$, $p = 0.29$, $\eta_p^2 = 0.04$. Neither middle nor late accuracy ($M = 95.9\% \pm 2.3$, $95.8\% \pm 2.3$) differed from early accuracy ($95.3\% \pm 2.9$); $t(31) = -1.23$, $p = 0.23$, $d = 0.22$, $BF = 0.37$, $t(31) = -1.34$, $p = 0.19$, $d = 0.24$, $BF = 0.43$, respectively. This indicates that during middle repetitions, when familiarity with the search targets had increased, participants were faster to find the targets without making more errors. During late repetitions there was a nonsignificant trend in the same direction. That the effect disappeared for late repetitions indicates our manipulation of VWM load was not very strong, or perhaps our analytic design of grouping repetitions dampened a critical element (see Discussion).

Incidental memory

Recognition accuracy for images previously presented as distractors during visual search was well above chance (Figure 5). Because distractors were only presented during a specific repetition of each visual search target (e.g., repetition 1, 6, or 10) we analyzed the effect of repetition stage (early, middle, or late) on recognition accuracy. A repeated measures ANOVA revealed no significant effect of repetition stage on recognition accuracy, $F(2, 62) = 1.74$, $p = 0.18$, $\eta_p^2 = 0.05$. Recognition accuracy for distractors seen during early ($M = 75.9\% \pm 12.7$) target repetitions in visual search was statistically indistinguishable from accuracy for middle- or late-stage ($72.4\% \pm 12.5$, $73.3\% \pm 8.5$) distractors; $t(31) = 1.81$, $p = 0.08$, $d = 0.32$, $BF = 0.81$, $t(31) = 1.27$, $p = 0.21$, $d = 0.22$, $BF = 0.39$.

Dwell time

We analyzed the effect of subsequent memory (remembered or forgotten), taken from the surprise recognition test, on dwell time. We also analyzed the effect of repetition stage in which the distractor appeared (early, middle, or late; Figure 4). One

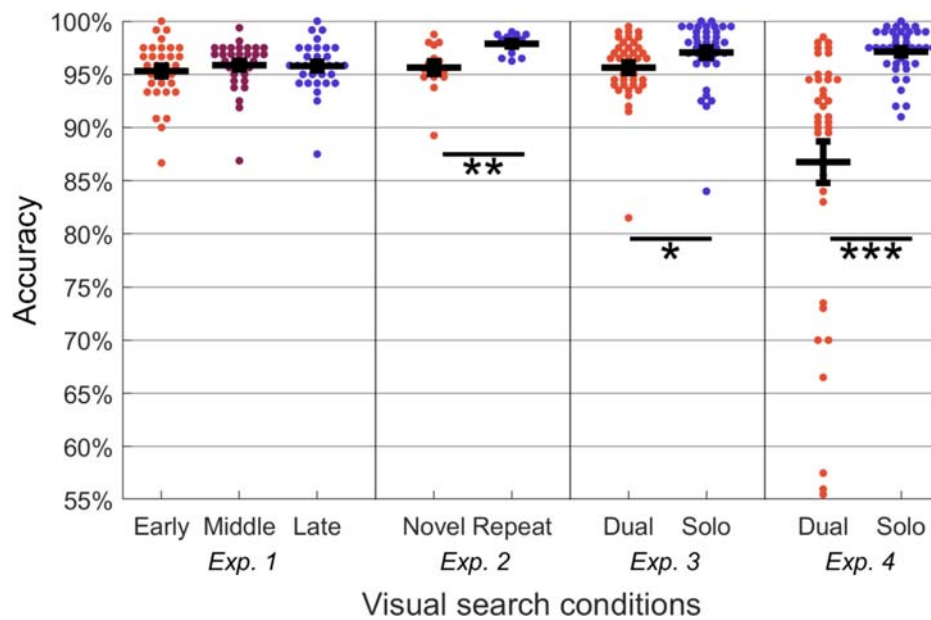


Figure 3. Visual search accuracy as a function of different search conditions across experiments. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

participant who remembered every early-stage distractor was excluded from these analyses because this led to a missing dwell-time value for forgotten early-stage distractors, resulting in n equal to 31. Subsequent memory and repetition stage were entered

as factors in a two-way repeated-measures ANOVA for dwell time. The effects of subsequent memory and repetition stage were both significant, $F(1,30) = 16.231$, $p < 0.001$, $\eta_p^2 = 0.35$, and $F(2,60) = 3.715$, $p = 0.03$, $\eta_p^2 = 0.11$, respectively, although their

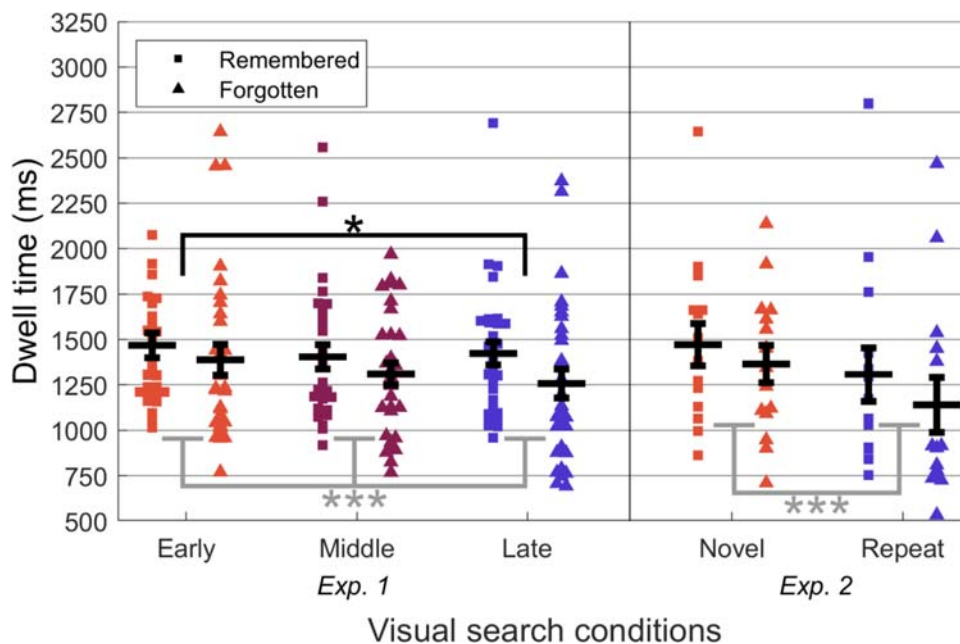


Figure 4. Dwell time on remembered and forgotten visual search distractors encountered during different experimental conditions. Based on the incidental recognition test, each distractor was back-sorted as remembered or forgotten. Each participant is represented by both a square (remembered) and a triangle (forgotten) for each condition in which they participated because all participants remembered some and forgot other distractors (except for one who remembered all distractors in the Early phase and was excluded here and in dwell time analyses for Exp. 1). Black comparison line indicates significance of pair-wise test between search conditions. Grey comparison lines indicate significance of main effect of memory. * $p < 0.05$. *** $p < 0.001$.

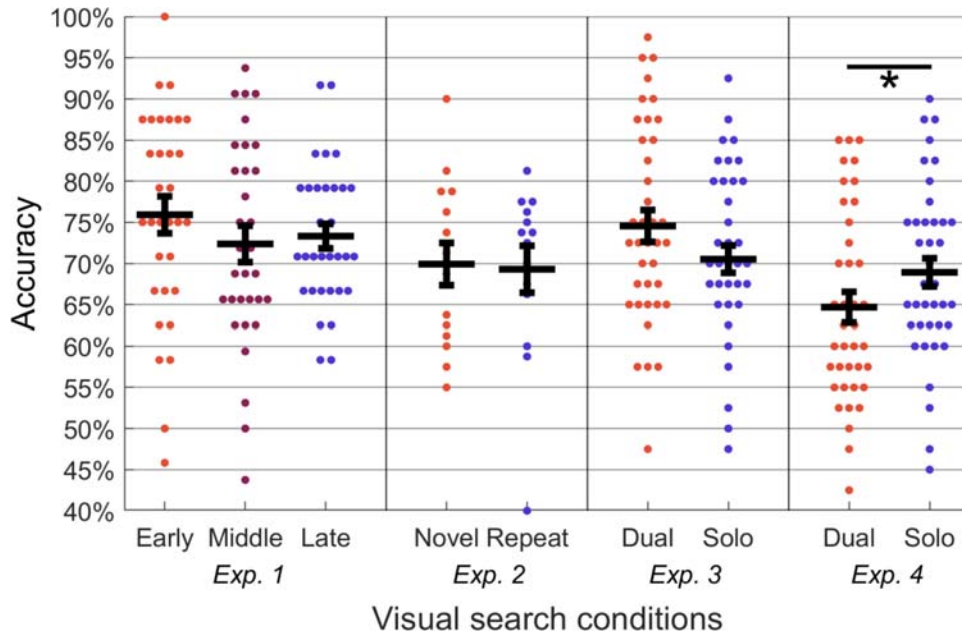


Figure 5. Recognition accuracy for distractors viewed during visual search under different conditions across experiments. * $p < 0.05$.

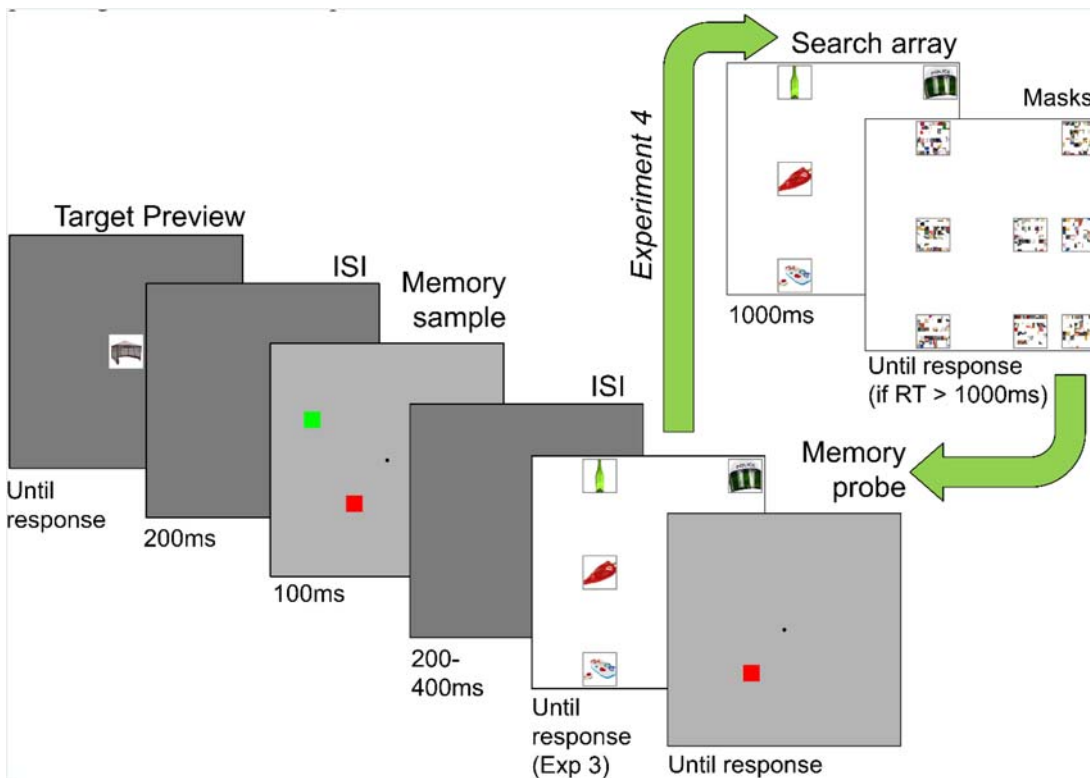


Figure 6. Visual search and change detection dual-task layout. The 500–700 ms interval from search initiation to search array onset matches the interval in the search alone condition. In Experiment 3 the search array was replaced by the change detection probe immediately following the response. In Experiment 4 the search array stayed on screen for at least 1000 ms, after which masks covered search items and remained on screen until response. Masks only appeared on trials when responses were slower than 1000 ms.

interaction was not, $F(2,60) = 0.857$, $p = 0.43$, $\eta_p^2 = 0.03$, $BF = 0.41$.

Subsequently remembered distractors were viewed for longer over the course of visual search than were subsequently forgotten distractors ($M = 1431.9$ ms \pm 358.3 and 1318.5 ms \pm 370.6, respectively); $t(30) = 4.03$, $p < 0.001$, $d = 0.72$. Distractors that appeared during early repetitions of targets were viewed for longer than those that appeared during late repetitions ($M = 1428.0$ ms \pm 403.0 and 1340.4 ms \pm 377.2, respectively); $t(30) = 2.53$, $p < 0.05$, $d = 0.45$. The difference between dwell time for early and middle repetition distractors (1357.2 ms \pm 334.1) was not significant, $t(30) = 1.93$, $p = 0.06$, $d = 0.35$, $BF = 0.98$.

Discussion

Visual search on early repetitions of targets was slower compared to middle repetitions, which was not due to a speed-accuracy trade-off. As such, it appears that visual search on early repetitions was more difficult. One interpretation of this finding is that early repetitions must therefore have required greater engagement of VWM. As indicated by eye tracking, distractors appearing in early repetition stages were viewed for longer than distractors appearing in late repetition stages. Though subsequently remembered distractors were viewed for longer than forgotten ones, these early repetition distractors were not recognized significantly better than middle and late repetition ones. Having thus replicated conditions that should have led to better encoding of early stage distractors, we did find weak evidence in favour of the hypothesis that VWM load does not improve such encoding.

Evidence in favour of the benefits of VWM load on encoding may have been obscured by the failure of our analytic design to capitalize on the most important stage of repetition-related changes in visual search. The changes are largest from repetition one to repetition two, in terms of speeding reaction time (but see Williams & Drew, 2018), improving accuracy (Williams & Drew, 2018), and reducing CDA magnitude (Drew et al., 2018; Servant et al., 2018; Woodman et al., 2013). Unfortunately, our design required grouping repetitions one, two, and three together into an “early” repetition phase, thus preventing a comparison between repetition one and

repetition two, or of repetition one by itself to middle or late repetitions. Eight unique distractors were assigned to appear during each of the 10 target repetitions, such that a given distractor (e.g., a carrot) only appeared on the n th time each target repeated, n being fixed for a given distractor. A comparison of the incidental encoding of eight distractors from repetition one to the eight distractors from repetition two, or any number of distractors from any group of repetitions, would likely be unreliable due to the small number of repetition-one distractors. As the VWM demands of representing the target template appear the greatest when the target is novel to the observer, the most advantageous comparison would take this first exposure as the reference against other repetitions. This is the basis of Experiment 2, where one group never searched for the same target twice and the other group searched for only one target across the entire experiment.

Experiment 2: novel or repeated targets

Method

In Experiment 2 we had one group of participants search for a new target on every trial (Novel group), eliminating repetitions of any targets. This should have forced participants to engage the maximal VWM resources possible in our single-target visual search. This allowed us to expose participants to a full set of 80 distractors while they were under this relatively high VWM load. The other group of participants searched for only one target throughout the course of the experiment (Repeat group), meaning that participants viewed all 80 distractors while VWM demands should have been minimal. In a between-subjects design, we tested whether the Novel group would perform better on the incidental memory test than the Repeat group.

Participants

Fifteen participants completed Experiment 2 in the Novel group, with a mean age of 20.5 ± 2.4 (6 males). An additional three participants were consented for the study but were excluded from analyses for the following reasons: a malfunction with the keyboard and failure to properly calibrate the eye tracker. Fourteen participants completed Experiment 2 in the

Repeat group, with a mean age of 23.4 ± 5.3 (4 males). An additional seven participants were consented but not analyzed for the experiment because of issues with calibrating the eye tracker, head motion, or because of an administrative error.

Design and procedure

The following aspects of the experiment were changed from Experiment 1. For the Repeat group in Experiment 2, only one target was used for the entirety of visual search. For the Novel group in Experiment 2, there was a new target for every visual search trial resulting in 400 target objects. The VWM factor was between subjects in analyses of search performance, dwell time, and distractor recognition. Measures were compared between the Repeat and Novel target groups. For distractor recognition, accuracy was computed as the percentage of correct responses out of the 80 2AFC distractor recognition trials. With group sizes of 14 and 15, Experiment 2 achieved 76% power for an independent samples *t*-test on distractor recognition, assuming the same effect size as the smallest reported across experiments in Hout and Goldinger (2010, 2012), $d = 1.03$ (see Experiment 1 Methods).

All other procedures and materials are identical to Experiment 1.

Results

Visual search

We compared reaction times (Figure 2) and accuracy (Figure 3) on the visual search task of participants who searched for the same target on every trial to those participants who searched for a new target on every trial. Searching for the same target for all 400 visual search trials instead of searching for a new target every trial did not speed reaction times significantly, $t(27) = -1.24$, $p = 0.22$, $d = 0.46$, $BF = 0.62$, $M = 702$ ms \pm 226 and 794 ms \pm 169 respectively. However, search accuracy did improve when the target stayed the same compared to when it changed every trial, $t(27) = 3.39$, $p < 0.01$, $d = 1.26$, $M = 97.9\% \pm 1.0$ and $95.6\% \pm 2.3$, respectively. As in Experiment 1, greater familiarity with the search target did slightly improve visual search performance,

though in this case the benefit manifested in increased accuracy with reaction time unaffected.

Incidental memory

As in Experiment 1, we compared memory for distractors using a surprise memory test after the search task (Figure 5). Recognition accuracy for distractors was statistically equivalent for the Novel ($M = 69.9\% \pm 10.0$) and Repeat ($69.3\% \pm 10.7$) groups: $t(27) = 0.16$, $p = 0.87$, $d = 0.06$, $BF = 0.35$. Thus, it appears that the increased demands of searching for a novel versus a familiar target does not boost incidental memory for distractors encountered during visual search.

Dwell time

We compared cumulative dwell time on each distractor image that appeared in visual search both between and within subjects (Figure 4). The between-subject comparison evaluated distractor dwell time for the Novel group versus the Repeat group. The within subject comparison evaluated whether distractors that were subsequently recognized were viewed longer, cumulatively, than those that were forgotten. Subsequent memory and target consistency group were entered into a two-way mixed-effects ANOVA. Participants spent significantly more time fixating distractors they subsequently remembered than those they forgot, $F(1,27) = 16.6$, $p < 0.001$, $\eta_p^2 = 0.38$, $M = 1392$ ms \pm 499 and 1256 \pm 491. Dwell time on distractors did not differ between the Novel and Repeat groups, $F(1,27) = 1.17$, $p = 0.29$, $\eta_p^2 = 0.04$, $BF = 0.73$, $M = 1418$ ms \pm 421 and 1223 ms \pm 555. There was no significant interaction between subsequent memory and target consistency, $F(1,27) = 0.80$, $p = 0.38$, $\eta_p^2 = 0.03$, $BF = 0.93$.

Discussion

We replicated the well-established observation that participants spend more time during visual search fixating distractors that are later recognized than those later forgotten (Hout & Goldinger, 2012; Williams, 2010b; Williams et al., 2005) in Experiments 1 and 2. This effect did not interact appreciably with VWM load during search. However, because the manipulations of target familiarity and novelty in these two experiments had no effect on distractor

encoding, we were not able to resolve questions regarding the relative importance of dwell time for encoding in relation to other factors relevant to long-term memory of search images. For example, Williams et al. (2005) found that search items garnering the best and worst subsequent recognition – targets on the one hand and distractors sharing no perceptual features with the target cue on the other – were not encoded better or worse depending on dwell time. Thomas and Williams (2014) suggest that finding the target may serve as a discrete episode that supports incidental encoding with such a large influence that dwell time plays no discernable role. We leave it up to future investigations to delineate the types of search in which dwell time does or does not matter for incidental encoding.

We were surprised at the modesty of the effects of search group on visual search performance and gaze behaviour. The electrophysiological literature regarding template-related VWM demands in repeated search contexts indicates the Novel group experienced a reliable VWM load (e.g., Drew et al., 2018; Woodman et al., 2013), and that the Repeat group may have totally offloaded the template from VWM (Carlisle et al., 2011). Although distractor encoding did not improve for observers maintaining one target template in VWM compared to essentially no target template in VWM, prior work suggests that maintaining two templates compared to one improves encoding (Guevara Pinto & Papesh, 2019; Hout & Goldinger, 2010, 2012). It is unlikely this manipulation of target repetition and novelty failed to place sufficiently different demands on VWM to affect a difference in subsequent distractor recognition. Instead, the missing ingredient from our first two experiments appears to be either (1) a large overall VWM load or, (2) a difference between conditions in the quality of guidance toward the target, which can be related to VWM load (e.g., Hout & Goldinger, 2010) but can also be independent of VWM load. To rule out the first possibility we conducted Experiment 3 using a dual-task paradigm to place participants under a higher VWM load.

Experiment 3: novel search with a VWM load

Experiment 3 was designed to manipulate VWM load to a greater extent than Experiments 1 and 2 by having subjects perform change detection simultaneous to visual search. Each subject completed 200

trials of visual search alone (low VWM load condition) and 200 trials of a dual-task condition where search was performed while holding information in VWM (high VWM load condition; see Drew et al., 2016, for a similar approach). If higher VWM load is responsible for the better incidental distractor encoding reported by Hout and Goldinger (2010, 2012), Guevara Pinto and Papesh (2019), and Guevara Pinto et al. (2020) in multiple-target search compared to single-target search, we would expect that participants would better encode distractors viewed during simultaneous visual search and change detection than during visual search without a secondary VWM task.

The inclusion of a secondary task likely engages VWM in a fundamentally different way than multiple-target search because only a portion of the maintained contents will be relevant at a given time. Under such task demands, it appears that observers can compartmentalize the contents of VWM into an active “attentional set” and a background of “accessory memory items;” the former act as a target template to guide visual search, the latter are maintained for use in delayed search or memory tasks (Olivers et al., 2011). Experimental support for this functional segregation of VWM comes from studies of the factors leading to or preventing automatic attentional capture of stimuli matching the contents of VWM. As reviewed by Olivers (2009), many factors influence such attentional capture, but holding search target features in VWM in a dual-task paradigm appears to suppress attentional capture by features maintained for a delayed task. Similarly, when observers are expecting a memory task to follow a search task, thereby reducing the relevance of the memory task features during search, distractors matching the features of the memoranda capture attention to a lesser extent than when participants cannot predict whether the memory or search task will come first (Olivers & Eimer, 2011). The present experiment should allow for compartmentalization of the change-detection sample during search, allowing observers to restrict the attentional set to the cued search target. Therefore, any degradation of search performance during the dual-task should have much less to do with ineffectiveness of the target template compared to multiple-target search, wherein no VWM compartmentalization is possible because any of the cued targets could be relevant for target detection. Target-distractor resemblance is

equated between dual- and solo-tasks because participants searched for a single, novel target on every trial. Given these differences between multiple-target search and a dual-task, Experiment 3 provides a strong test of the generality of potential benefits VWM load confers to incidental distractor encoding.

Method

Participants

Thirty-nine participants completed Experiment 3, with a mean age of 21.5 years \pm 3.1 (nine males). An additional eight participants were consented for the experiment but were not analyzed. Five of these were excluded because they did not perform above chance levels on change detection (56.5% accuracy; see Method subsection "Analysis"). Another was excluded due to excessively slow reaction times during visual search in both conditions. While the mean RTs in the dual- and solo-tasks were 1903ms \pm 759 and 845 ms \pm 148 (after excluding this participant), respectively, this participant's means were 5001 ms and 1833ms. One participant was dismissed for advancing too slowly through the task and using his hands as a mnemonic aid for change detection. A final participant was excluded for being older than the upper bound of our age requirement.

All procedures and materials are identical to Experiments 1 and 2 unless otherwise noted.

Design

Participants completed the dual-task during either the first 200 or last 200 trials, counterbalanced across participants. The change detection task (Figure 6) required participants to remember the colour and location of four squares presented on the screen for 100 ms. After a delay (during which participants completed visual search), a single probe square was displayed in the same location as before. Half of the time the probe was the same colour as the square from the memory array previously located in that position. Participants indicated with the keyboard whether the colour of the probe was different from the corresponding square in the memory array. The colours of the squares were randomly sampled with replacement from black, white, blue, red, green, or yellow. Each square appeared in

different quadrants of the screen. Additionally, there was a small black oval in the centre of the screen for the memory array and memory probe displays. Participants were given feedback on the accuracy of their response to the change detection task in addition to the visual search task.

The change detection task was interleaved with visual search in the following way. As before, participants viewed their target until pressing space bar to begin the visual search. Once the participant initiated the trial, a blank screen appeared for 200 ms preceding the change detection sample, which was displayed for 100 ms. Following this, a blank screen was again displayed for a random duration between 200 ms and 400 ms. Then the visual search array appeared until response. Immediately following that, the change detection sample appeared and remained on screen until response. Then feedback was displayed for 638 ms. Thus, the delay of the search array from the time participants initiated the trial was randomly distributed between 500 and 700 ms, as in the previous experiments. Feedback duration was also the same as Experiments 1 and 2.

Half of the distractor sets were used for trials 1-200, and the other for trials 201-400. This allowed us to separately compare the memory for distractors that appeared while participants completed either visual search simultaneous to change detection or visual search alone. Each distractor set was used every five trials, but after 200 trials each set was replaced with a new one. For example, distractor set 1 was used on trial 1, 6, 11, and so on, while distractor set 6 was used on trial 201, 206, 211, and so on.

Procedure

Participants completed the study without eye tracking in a room with multiple testing stations separated into cubicles, allowing up to 3 participants to complete the study at the same time. Participants were instructed to prioritize the change detection task higher than the visual search task. This was to counteract the trend we observed during piloting where participants neglected the change detection task in favour of visual search, such that their change detection performance was not above chance. The cover story was also somewhat different from Exps. 1 and 2 in explaining that we wanted to know how well participants could detect change in visual information

while multitasking. Participants indicated with the keyboard whether the colour of the probe had changed or not. The “F” key indicated the colour remained the same, “J” indicated it changed. These instructions were on screen while the memory probe was displayed. Key assignment was also displayed during visual search to prevent confusion that may arise in the dual-task setting.

Apparatus

Experiments 1 and 2 used a different computer monitor from Experiment 3. There were miniscule differences in visual angles subtended by the experimental displays. Note, however, that Experiments 1 and 2 used a chinrest for eye tracking, but in Experiment 3 there was no chin rest thus viewing distances are approximated at 60 cm. The white background for the search array was reduced to 17.3° by 17.3° of visual angle to allow room for onscreen text to indicate response key assignment during visual search. The colourful squares used for change detection measured 1.2° . The small black circle centred on the screen measured 0.1° . The area in which the colourful squares could appear had a lighter grey background than the rest of the screen. This area was a centred rectangle 66% of the size of the monitor, subtending 30.3° by 17.0° .

Analysis

Visual search and distractor recognition performance were compared within subjects with the VWM factor of dual- versus solo-task condition. There were 40 2AFC recognition trials for distractors appearing in the dual- and solo-task, respectively. Experiment 3 exceeded 99% power to detect a distractor recognition effect of $d = 1.03$ (Hout & Goldinger, 2010, Exp. 1) with a dependent samples *t*-test for a sample size of 39.

To ensure that participants had carried a higher VWM load in the dual-task condition, we estimated the level of chance performance on change detection and eliminated participants from analyses if they did not exceed that level. The probability of correctly guessing on 114 (57%) or more trials was less than 0.05, according to the binomial cumulative distribution function with 200 trials and 0.5 probability of success. We considered all scores equal to or below 56.5% as chance performance. In Experiments 3 and

4 we estimated VWM capacity (K) using the formula $K = (\text{Hit Rate} - \text{False Alarm Rate}) * N$, (Cowan, 2001) where N (set size) was fixed at four. This allowed us to determine if participants were reaching their VWM capacities or if they were potentially performing sub-optimally via comparison with the average K for set size four estimated from a sample of roughly 3,900 change detection datasets (Balaban et al., 2019). The estimate from Balaban et al. (2019) is our best guess at the population mean for a university sample, with K equal to 2.79, though we note different samples report slightly higher and lower estimates (see Dai et al., 2019; Xu et al., 2018).

Results

Change detection

Of the 39 participants who completed change detection adequately, the mean accuracy and RT were $70.2\% \pm 8.7$ and $1299 \text{ ms} \pm 335$, respectively. This corresponded to an average estimated capacity (K) of 1.62 ± 0.70 . Prior work that compared change detection performance with and without a search task embedded during the delay period suggested that this task resulted in a reduction of approximately one item in K (Drew et al., 2016). If we assume that this is the case here, the functional K participants demonstrated is roughly 2.6. This is slightly below the average K for a visual set size of four taken from a large-sample study of university students and members of the community at large ($K = 2.79$; Balaban et al., 2019). Importantly, this suggests that most participants were utilizing their VWM to its maximum capacity in order to effectively engage visual search and change detection simultaneously. This allays any concerns that the VWM load manipulation was too modest to elicit a distractor encoding effect.

Visual search

We compared reaction times (Figure 2) and accuracy (Figure 3) on the visual search task within-subject, between the dual-task condition and the search alone condition. Completing change detection significantly slowed search, $t(38) = 8.69$, $p < 0.001$, $d = 1.39$, $M = 1903 \text{ ms} \pm 759$ and $845 \text{ ms} \pm 148$. Visual search accuracy also suffered as a consequence of simultaneous change detection, $t(38) = -2.67$, $p < 0.05$, $d = 0.43$, $M = 95.6\% \pm$

3.1 and $97.1\% \pm 3.1$ for the dual- and solo-tasks, respectively. Whereas the manipulations of WM during visual search in previous experiments affected either accuracy (Exp. 2) or reaction time (Exp. 1), the present dual-task vs search alone manipulation both slowed search and reduced its accuracy.

Incidental memory

Separate distractors appeared during the dual-task condition compared to the search alone condition. This allowed us to perform a within-subjects comparison of the effect of visual search condition (dual-task versus search alone) on incidental memory for distractors (Figure 5). There was a marginally significant benefit in recognition accuracy for dual-task distractors as compared to search alone distractors: $t(38) = 1.89$, $p = 0.07$, $d = 0.30$, $BF = 0.86$, $M = 74.6\% \pm 12.1$ and 70.5 ± 10.4 . This was not due to a speed accuracy trade-off on the surprise recognition test as RTs were equivalent, $t(38) = -1.02$, $p = 0.32$, $d = 0.16$, $BF = 0.28$, $M = 1703\text{ms} \pm 395$ and $1758\text{ms} \pm 448$ for the dual- and solo-tasks, respectively.

Discussion

The purpose of the present experiment was to evaluate whether the effects reported by Hout and Goldinger (2010, 2012) and others depend mainly on the sheer VWM load in search for three compared to one target, or whether boosted incidental distractor encoding depends more on target template and distractor similarity factors. The results of Experiment 3 suggest that a VWM load is not sufficient to increase distractor recognition or decrease visual search accuracy. It appears that single-target search with secondary VWM load does not impact search accuracy relative to baseline (1.5% reduction) as much as three-target search does from Hout and Goldinger (2010, 2012) Experiments 1 (6.6% and 3.6% reductions, respectively). Nor does the marginal distractor recognition boost from the dual task (4.1%) appear to be as large as the significant boosts from three-target search (11% and 12%) from Hout and Goldinger's (2010, 2012) Experiments 1, respectively. It is fair to assume (and reflected in the accuracy data) that three-targets exceeded participants' VWM capacity (e.g., $K = 2.79$; Balaban et al., 2019) in Hout and Goldinger (2010, 2012) and thus, those

participants carried a similar working memory load to participants in the present dual-task (estimated functional capacity $K = 2.6$). However, the lack of a substantial accuracy effect or significant recognition boost suggests a VWM load in itself does not account for the findings of Hout and Goldinger (2010, 2012) and others. Although it is not clear whether the target template was completely intact during search, prior research suggests that participants were able to minimize a potentially deleterious effect of the irrelevant memory sample on search guidance by compartmentalizing the representation of the VWM load during the search task (Olivers, 2009; Olivers & Eimer, 2011). In multiple-target search, although only a single target may appear out of the two to four cued images (but see Guevara Pinto et al., 2020), observers must represent all potential targets because any one could appear during search. This likely causes broader search and greater scrutiny of distractors, thereby aiding distractor encoding. Thus, our data suggest that because the memory sample could be relegated during search in Experiment 3, accuracy was mostly preserved and observers did not seem to scrutinize or remember distractors greater during the dual-task than search alone. Returning to the possibilities raised by Experiment 2, it appears the missing encoding ingredient in Experiments 1 and 2 was impaired search guidance related to template precision and/or target-distractor similarity, rather than the VWM load exceeding one item. The VWM load in the Experiment 3 dual-task condition clearly exceeds two items, but because search guidance was likely preserved we again obtained null results in distractor recognition.

To rule out the possibility that the dual-task simply was not difficult enough to induce adequate scrutiny of distractors, we imposed a time-limit on visual search in Experiment 4, otherwise replicating the methods of Experiment 3.

Experiment 4: fixed exposure search with a VWM load

Method

We fixed stimulus exposure to search arrays in Experiment 4 to see if increased search difficulty in the dual-task would facilitate incidental distractor encoding. Regardless of reaction time, the search array

appeared for 1000 ms on every trial (see [Figure 6](#)). We chose 1000 ms as a close approximation of the mean RT in target-absent trials in the search alone condition of Experiment 3 ($M = 956$ ms). If participants responded slower than 1000 ms, each image in the search array was replaced by a unique mask that remained on the screen until the participant responded.

On every trial eight masks were randomly assigned to the image locations in the search array. Ten masks were created from 120 source images that were originally in the pool of images available for random assignment to target, practice, or foil categories. These images were randomly selected and removed from that pool. Each mask is composed of 64 square segments, rotated at random integer multiples of 90° , extracted from the source images without replacement (see [Figure 6](#)).

Unless otherwise noted, the methods of Experiments 3 and 4 were identical.

Participants

Thirty-nine participants completed Experiment 4, with a mean age of 20.7 years ± 3.5 (16 males). An additional 21 participants were consented for the experiment but were not analyzed due to poor performance on the change detection task (below 56.5% accuracy). With the additional pressure of masks appearing after 1000 ms during visual search, many participants struggled to complete both, or either, task effectively. Another participant was excluded from analyses for performing below chance on visual search. Three other participants were excluded due to computer malfunction during the experiment. In total, 25 participants were consented but not analyzed.

Results

Change detection

Average accuracy and RT on the change detection task simultaneous to visual search were $66.4\% \pm 6.6$ and 1221 ms ± 272 . Estimated K was 1.31 ± 0.53 . Assuming, as we did for Experiment 3, that the visual search task reduced our estimate of K by roughly one item (Drew et al., 2016), the function K participants demonstrated is roughly 2.3. This is

slightly lower than average K from a large sample ($K = 2.79$; Balaban et al., 2019), but similar to Experiment 3. It appears that participants recruited substantial VWM resources during the dual-task condition.

Visual search

As in Experiment 3, we analyzed reaction times ([Figure 2](#)) and accuracy ([Figure 3](#)) for visual search within subjects, comparing performance between the dual-task and the search alone conditions. Reaction times were significantly slowed in the dual-task condition compared to search by itself, $t(38) = 8.46$, $p < 0.001$, $d = 1.35$, $M = 1323$ ms ± 377 and 836 ms ± 174 . Visual search accuracy was also reduced when participants completed simultaneous change detection compared to when they solely completed search, $t(38) = -5.69$, $p < 0.001$, $d = 0.91$, $86.7\% \pm 12.2$ and $97.1\% \pm 2.2$.

Incidental memory

Repeating our analyses from Experiment 3, we assessed the within-subjects difference in incidental memory for distractors that appeared in either the dual-task condition or the search alone condition ([Figure 5](#)). Distractors that appeared during the dual-task condition were significantly less likely to be recognized than those that appeared during the solo-task condition, $t(38) = -2.29$, $p < 0.05$, $d = 0.37$, $M = 64.7\% \pm 11.6$ and $68.9\% \pm 10.7$ for dual and solo conditions, respectively.

The time limit placed on search raises the possibility that visual search accuracy and incidental encoding suffered not from VWM load (or maintenance) itself but from a delay in search initiation due to VWM consolidation. The stimulus onset asynchrony (SOA) in Experiment 4 was uniformly distributed between 300 and 500 ms, with less than 1.5% of trials having an SOA duration of 283 ms and 1.2% having a duration between 500 and 533 ms due to timing errors. Using a sample memory duration (100 ms) that was identical to the current work, Vogel et al. (2006) demonstrated that working memory capacity for a set size of four appears to plateau with an SOA of 183 ms between sample onset and mask onset, with no change-detection performance gains for longer SOA of 267 ms or 317 ms. Thus, participants should have had adequate time to

consolidate the memory sample before the search array appearance. If consolidation took longer than 300 ms we would expect search accuracy to improve at longer SOA. In a control analysis predicting single-trial error responses with a generalized linear mixed model using the logit link (glmer function in the lme4 package for R, Bates et al., 2015; R Core Team, 2018) we found no evidence that the probability of errors significantly decreased with longer SOA. The predicted decline in probability of errors was 1.2% from the shortest (283 ms) SOA to the longest (533 ms), $p = 0.21$ for the SOA coefficient.

Discussion

The stimulus presentation time limit was successful in increasing the difficulty of the dual-task condition. In Experiment 3, participants compensated for reduced search-dedicated VWM capacity by searching for longer, although dual-task accuracy still suffered compared to the solo-task. Limiting search array visibility to 1000 ms removed the possibility for this compensatory, slowed search in Experiment 4. That dual-task RTs in Experiment 4 were much lower than Experiment 3 (Figure 1) suggests participants were terminating search prematurely in Experiment 4, potentially because they had not arrived at a decision before the appearance of masks but spending further time deliberating (no longer searching) afforded no benefit to performance. Our dual-task manipulation of VWM load resulted in a vastly different pattern of results than prior work that has varied the number of potential search targets. Whereas multiple-target search boosted recognition over single-target search by 11% and 12% in Hout and Goldinger's Experiments 1 from 2010 and 2012, we found that dual-task search significantly *impaired* recognition by 4.2%. This clearly suggests that the small, marginally significant benefit for distractor recognition in the dual-task condition observed in Experiment 3 was driven by the greatly increased RT for the dual-task trials rather than an increased proclivity to encode distractor information under conditions of VWM load.

The combined results of Experiments 3 and 4 reveal a differential dependency of distractor encoding on stimulus exposure duration between VWM load owing to a dual-task and that owing to multiple-target search. Whereas the benefit to distractor encoding of multiple target search persists under

circumstances of equated stimulus exposure via Rapid Serial Visual Presentation (Guevara Pinto & Papesch, 2019; Guevara Pinto et al., 2020; Hout & Goldinger, 2010), the marginal boost to distractor encoding was significantly reversed when search array duration was equated between dual- and solo-tasks. In summary, factors distinct from, but related to, VWM load, appear to be responsible for the boosted incidental encoding that others have reported but we failed to find.

General discussion

Across four experiments that manipulated VWM load during visual search, we observed no evidence for a unique benefit that VWM load itself confers to incidental encoding of distractors. Prior work from Hout and Goldinger (2010, 2012), Guevara Pinto and Papesch (2019), and Guevara Pinto et al. (2020) has manipulated VWM by cueing between one and four potential targets. In contrast, the current study controlled for one or both of the crucial factors that are influential over distractor encoding and implicated in these previous studies: target-distractor similarity and target template effectiveness. Target-distractor similarity was equated across VWM load conditions by holding the number of potential targets constant at one in all experiments. Target template effectiveness was controlled by using only novel targets in our comparison of dual-task to search alone (Experiments 3 and 4). Manipulating participants' familiarity with the target via target repetition (Experiments 1 and 2) potentially affected template effectiveness, but using this technique for altering VWM demands was important to test the influence of VWM on distractor encoding in a wider array of search tasks than has so far been reported. We found further support in these experiments for the hypotheses that multiple target search improves incidental distractor encoding through increased opportunity for target-distractor similarity (e.g., Williams, 2010a; see Guevara Pinto et al., 2020) and reduced template effectiveness (Guevara Pinto & Papesch, 2019). As regards prior work from Hout and colleagues, this suggests that previously observed association between target template effectiveness and distractor processing is independent of VWM engagement.

Experiment 3 suggests that not all VWM loads are created equal in terms of their detriment to search

performance and benefit to incidental encoding. Olivers (2009) and colleagues (Olivers et al., 2011) have already demonstrated observers' abilities to pay differential attention to the contents of VWM, allowing different features to guide search or memory tasks at the appropriate time (Olivers & Eimer, 2011). Three-target search (e.g., Hout & Goldinger, 2010) and the dual-task of Experiment 3 likely imposed comparable demands on VWM, but accuracy in the dual-task was only slightly reduced compared to search alone. Search accuracy effects and distractor recognition benefits were larger in prior reports of three-target search. Experiment 4 indicates the failure to replicate the distractor encoding benefit was not a result of the task being too easy, or, rather, that the dual-task cannot be made any more difficult without negatively impacting distractor encoding. This constrains our proposed interpretation of Experiments 1 and 2 that VWM load only improves distractor encoding after a two-item threshold has been reached. It is more likely that there must be at least two *search-relevant* items in VWM to improve distractor encoding. Otherwise irrelevant contents of VWM can be deprioritized during search. In this deprioritized state, the VWM contents may minimally harm search guidance, meaning distractors would be spared from the requisite scrutiny to be incidentally encoded. Further, when searching for a single target it may not matter whether the attentional set is maintained in VWM or LTM – encoding and recognition of distractors appears to be the same. As a corollary, while the threshold for improved encoding may be two targets, they need not be maintained in VWM. Assessing incidental distractor encoding during the hybrid search paradigm (Wolfe, 2012) would be a promising method to test this hypothesis, as described next.

The present study attempted to isolate the role of VWM in distractor encoding by holding the effectiveness of the target template constant. A complementary approach would be to isolate the role of the effectiveness of the target template by holding VWM load constant during search. This could be achieved through hybrid search by having participants memorize different sets of targets before beginning visual search for those targets amongst different sets of distractors. Incidental distractor recognition could be assessed as a function of the memory set that was active when certain distractors appeared. It

has already been established that VWM demands of hybrid search are stable across memory set sizes of two, eight, 16, and 64 (Drew et al., 2016). The effectiveness of the template can be manipulated by varying the memory set size (Drew et al., 2017) without affecting VWM demands. Manipulating target-to-target resemblance within a memory set may also serve to alter template effectiveness. While this has yet to be tested in hybrid search, visually similar targets do foster effective target templates held in VWM (Hout & Goldinger, 2015), potentially by restricting the intervals of the salient visual dimensions (e.g., colour, size; Menneer et al., 2009). Target-distractor resemblance could also be manipulated orthogonally to target-target resemblance and memory set size. With a multitude of independent factors, an assessment of incidental encoding during hybrid search could prove very fruitful. First, it may further inform our understanding of the role of template effectiveness on incidental distractor encoding. Second, it may indicate how search through space and memory improves or deteriorates depending on the homogeneity of the memory set. Models of hybrid search (e.g., Cunningham & Wolfe, 2014) would benefit from such discoveries as they may shed light on features of the search array that capture attention, and undergo categorization and comparison with the memory set. Incidental memory could provide hints towards residual effects of this selection, categorization, and comparison. Finally, it could illuminate the influence of active visual memory sets on further, undirected encoding. Assessing incidental distractor encoding during hybrid search could establish, for example, whether memories are more easily formed when searching for a narrow or broad set of stimuli and whether the memory set facilitates encoding of similar or dissimilar distractors.

Conclusion

What and how we seek helps determine the images that find their way into our memory. The results of our four experiments suggest that the additional consumption of VWM by a novel search target or by extraneous information during search offers little to no direct aid in incidental encoding of distractors. When viewed from the vantage of VWM load during search, it is genuinely surprising that searching for

fewer numbers of target images impairs incidental encoding of distractors (Guevara Pinto et al., 2020; Guevara Pinto et al., 2020; Hout & Goldinger, 2010, 2012). But in light of our results, we favour the hypothesis that incidental distractor encoding benefits from ineffective target templates that lead to less directed search and stronger luring of attention by distractors. Our results also speak to the differential status that contents of VWM may take (Olivers et al., 2011) and why the size of the attentional set may be more relevant to distractor encoding than VWM load in general. Future research exploring incidental distractor recognition following hybrid search offers exciting avenues to hold VWM constant during search (Drew et al., 2016) and explore how templates committed to memory guide search and interact with undirected encoding.

Disclosure statement

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Data availability statement

All of the relevant data are published on the OSF website (doi: 10.17605/OSF.IO/ZFQXC). Additional data and scripts are available from the corresponding author upon request.

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