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RESEARCH REPORT

Interference Within the Focus of Attention: Working Memory Tasks Reflect More Than Temporary Maintenance

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One approach to understanding working memory (WM) holds that individual differences in WM capacity arise from the amount of information a person can store in WM over short periods of time. This view is especially prevalent in WM research conducted with the visual arrays task. Within this tradition, many researchers have concluded that the average person can maintain approximately 4 items in WM. The present study challenges this interpretation by demonstrating that performance on the visual arrays task is subject to time-related factors that are associated with retrieval from long-term memory. Experiment 1 demonstrates that memory for an array does not decay as a product of absolute time, which is consistent with both maintenance- and retrieval-based explanations of visual arrays performance. Experiment 2 introduced a manipulation of temporal discriminability by varying the relative spacing of trials in time. We found that memory for a target array was significantly influenced by its temporal compression with, or isolation from, a preceding trial. Subsequent experiments extend these effects to sub-capacity set sizes and demonstrate that changes in the size of k are meaningful to prediction of performance on other measures of WM capacity as well as general fluid intelligence. We conclude that performance on the visual arrays task does not reflect a multi-item storage system but instead measures a person's ability to accurately retrieve information in the face of proactive interference.

Keywords: working memory, attention, visual arrays, temporal discriminability

Working memory (WM) is often conceptualized as a cognitive system that provides dynamic storage and processing of information in the service of ongoing cognition (Miyake & Shah, 1999). For researchers who emphasize storage as the mechanism that gives rise to individual differences in WM capacity (e.g., Awh, Barton, & Vogel, 2007; Cowan et al., 2005; Vogel, Woodman, & Luck, 2001), WM has at least two critical properties that differentiate it from long-term memory (LTM). First, within WM, the *focus of attention*[1] is used to maintain information in a fully activated state (e.g., Cowan, 1999, 2001). Thus, information that is stored in WM is protected from retrieval-based competition (i.e., proactive interference). Second, WM has a fixed capacity of about four chunks of information (Cowan, 2001, 2010; Luck & Vogel, 1997). This estimate is assumed to vary among individuals (3–5 chunks) and to account for documented links between WM capacity and novel reasoning ability (i.e., general fluid intelligence [Gf]; Cowan et al., 2005; Fukuda, Vogel, Mayr, & Awh, 2010).

Much of the evidence for maintenance-based perspectives of WM has been collected via the visual arrays task (e.g., Luck & Vogel, 1997). This simple, but effective, computer-based measure of WM capacity begins with the brief presentation of an array of randomly arranged objects (e.g., colored squares), which is followed by a blank screen. After a short delay, the objects reappear. On this second presentation, one is encircled (i.e., probe item). The test-taker is required to decide whether this object has changed, relative to its initial presentation (e.g., has the square's color changed?).

Critical to storage-based accounts of WM capacity, accuracy is stable when the displays contain up to 3–4 items but steadily decreases as additional items are added (Luck & Vogel, 1997). Storage-based accounts of WM capacity interpret this trend as evidence that when the number of objects contained in a display exceeds the storage capacity of WM (referred to as k), it lowers the likelihood that any one array-item will be stored. Once corrections are made to account for array size (see the Design section in Experiment 1), it can be shown that people are capable of accu-

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[1] We use the terms "focus of attention" or "storage in WM" to refer to perspectives in either the tradition of Cowan (2001) or Luck and Vogel (1997). The former is concerned with modality-free storage, whereas the latter focuses on storage of visuo-spatial information. However, the present experiments have similar implications for both views.

rately responding to about four items, regardless of the total number of items contained within an array (Cowan et al., 2005; see also Pashler, 1988). The stability of this limit across array sizes has been taken as an indication that the average person's WM has four discrete slots; each of which is capable of maintaining one chunk of information in an interference-free state (Awh et al., 2007; Cowan, 2001, 2010; Rouder, Morey, Moray, & Cowan, 2011).

Other Perspectives

While maintenance-based perspectives provide a reasonable explanation of the visual arrays performance, basic issues remain underexplored. In particular, the assumption that visual arrays performance is strictly driven by stable maintenance in WM necessitates a further assumption that retrieval from LTM is not involved. If a person can accurately respond to four items, it is ostensibly because that person can maintain four items in WM.

However, within the broader scope of cognitive psychology, multi-item storage is controversial. For instance, WM studies that employ focus-switching (Garavan, 1998; Oberauer, 2002) and n-back tasks (McElree, 2001; Verhaeghen, Cerella, & Basak, 2004) find that performance is slowed when a person responds to anything other than the most recently presented item. These costs have been interpreted as reflecting the time needed to reorient a one-item attentional focus.

Carroll et al. (2010; see also Hanley & Scheirer, 1975) reported that when participants are required to remember a series of three item lists, recognition response times increase on a trial-by-trial basis. That is, buildups of proactive interference occur even for amounts of to-be-remembered information that should fit within a four-slot focus of attention. Moreover, changing the type of stimuli contained on each list was associated with a release from proactive interference (cf. Wickens, Born, & Allen, 1963): When to-be-remembered items were changed from digits to non-words (thus reducing retrieval-based proactive interference), response times decreased.

Results such as these imply that WM is reliant on mechanisms other than temporary storage. For instance, Oberauer's (2002; Oberauer, Süß, Wilhelm, & Sander, 2007) concentric model of WM assumes that focal attention is limited to one item. The 3–5 item capacity proposed by Cowan (1999, 2001) and Luck and Vogel (1997) is reached via a "region of direct access" in which activated elements of LTM are contextually bound to focal attention. Although all information outside of the one-item focus is subject to interference (Oberauer & Kliegl, 2006; Oberauer & Vockenberg, 2009), the bindings afford privileged access to attention and allow for integration of disparate information. Thus, a critical determinant of individual differences in WM capacity is not absolute storage but the ability to manage the region of direct access through establishment and dissolution of contextual bindings (e.g., WM updating; Miyake et al., 2000; Wiley, Jarosz, Cushen, & Colflesh, 2011).

Unsworth and Engle's (2006, 2007) temporal-contextual model of WM assumes that the demands placed on WM often exceed 3–5 items, and thus individual difference in WM capacity also reflects accurate retrieval of information from LTM. Relevant to the present set of studies, Unsworth and Engle proposed that low WM capacity is associated with difficulty constraining searches of LTM to specific periods of time. This inaccurate cuing of time means that people with low WM capacity contend with greater proactive interference and a lower probability of retrieving critical information, relative to high WM capacity individuals. From this view, visual arrays performance is partially due to temporary storage but also reflects retrieval of information that cannot be maintained in primary memory.

Visual Arrays and Proactive Interference

Increased response times associated with attention-shifting (e.g., Garavan, 1998; McElree, 2001; Oberauer, 2002; Verhaeghen et al., 2004) and list retention (e.g., Carroll et al., 2010; Hanley & Scheirer, 1975) tasks favor single-item accounts of WM storage. However, these tasks feature serial order presentation and often use verbal material. The visual arrays task, on the other hand, presents visuo-spatial information in parallel. As such, single-item accounts of the focus of attention may specifically pertain to events that unfold over time (cf. McElree & Dosher, 2001) or within a specific modality (Luck & Vogel, 1997). Cowan, Fristoe, Elliot, Brunner, and Saults (2006) further resolved disparity by assuming that delayed response times represent prioritization of certain items above others within WM. Longer response times are interpreted as lower prioritization, rather than the time needed to shift the focus of attention.

It is therefore necessary to demonstrate the presence of proactive interference using tasks that are in the tradition of Cowan's (2001) and Luck and Vogel's (1997) theorizing. To date, a handful of studies have directly examined the influence of proactive interference on visual arrays performance. The results are interesting, but arguably equivocal.

Makovski and Jiang (2008) used a visual arrays task in which colored circles were presented at five spatially fixed locations. On some change-trials, the probe item's color matched that of the item that had been in that location on the preceding trial. That is, although an item did change, it changed to something that was potentially familiar. In these situations, participants were biased toward responding "no-change." Thus, Makovski and Jiang argued that no-longer-relevant information influences visual arrays performance.

While these results are intriguing (i.e., Makovski & Jiang, 2008), their generalizability is questionable (Lin & Luck, 2012). Visual arrays tasks typically rely on random selection of object characteristics and often present items in random patterns on a trial-by-trial basis. While Makovski and Jiang (2008) show that placing a familiar object in a critical location can influence responding, these situations are rarely encountered in practice and are therefore unlikely to have a systematic impact in most studies. Moreover, because Makovski and Jiang used displays with more than four items, it is unknown whether familiarity influenced information that participants were ostensibly maintaining in WM or whether the feeling of familiarity arose from outside of WM.

Hartshorne (2008), however, found that when a single probe is presented in the center of the screen (i.e., rather than its original location), change detection accuracy is significantly influenced by information from the last three trials (relative to a probe that was presented eight trials back). Additionally, while Makovski and Jiang (2008) used displays with five or more items, Hartshorne's arrays consisted of only three items. This amount of information should be easily stored within WM. Thus, familiarity effects are unlikely to have originated from outside of a traditional (e.g., Cowan, 2001) focus of attention.

A subsequent experiment (Hartshorne, 2008) demonstrated that when the category of display objects (e.g., colors, shapes) is switched, change detection accuracy increases (i.e., release from proactive interference; Wickens et al., 1963). These performance improvements then gradually disappear over the course of 10 subsequent trials and reoccur when the next category change is made.

Lin and Luck (2012) pointed out that the visual arrays tasks used by Hartshorne (2008) differed from standard versions in a number of ways. In particular, arrays were displayed for 1,000 ms, with a 1,000-ms delay between target and probe. Lin and Luck argued that this 2-s interval provided time for LTM representations to be formed and affect responding. These researchers thus halved the length of each trial by reducing the array presentation to 100 ms and the retention interval to 900 ms. Release from proactive interference did not occur under these conditions.

Although this finding may prove informative, there are other timing-related differences between the studies of Hartshorne (2008) and Lin and Luck (2012). We consider their potential impact following discussion of the present set of experiments.

The Present Study and Predictions

The present experiments employ a manipulation of temporal discriminability (Baddeley, 1976; Brown, Neath, & Chater, 2007; Crowder, 1976; Glenberg & Swanson, 1986; Neill, Valdes, Terry, & Gorfein, 1992). The intent is to reveal retrieval-based processes in visual arrays performance using a less explicit cue.

Figure 1 presents the two conditions used in Experiment 1. The box labeled “Previous Response” represents the end of any given trial. The participant’s response is immediately followed by an inter-trial interval (ITI), after which a new array of colored squares is presented. The offset of this “Target Array” is followed by an inter-stimulus interval (ISI) of equal duration to the ITI. The squares then reappear (i.e., Probe Array; see Figure 1), and the participant must decide whether the encircled square has changed color. The length of both the ISI and ITI were fixed between subjects at either 900 ms or 3,900 ms. Either condition is consistent with previous visual arrays studies, which have used fixed ISIs of lengths similar to the ones presently employed (cf. Cowan et al., 2005; Morey & Cowan, 2005; Vogel et al., 2001).

The intent of Experiment 1 was simply to demonstrate that a participant’s memory for an array will not decay as a product of the absolute length of the ISI (e.g., Vogel et al., 2001). This, of course, is consistent with WM-based storage. For instance, Cowan’s (1999, 2001) embedded process model assumes that WM contains a limited-capacity focus of attention, in which information is protected from time-based decay. Outside of the focus of attention, recently active units of LTM (referred to as short-term memory) are continually decaying toward baseline activation levels. Demonstration that visual arrays performance is not negatively affected by absolute time would therefore be explained by assuming that people respond based upon the contents of WM, without reliance on decay-prone short-term memory.

However, a lack of time-based decay is not uniquely predicted by storage in WM. Test-takers may also retrieve relevant information from LTM. Critically, Experiment 1 has been designed such that the absolute length of the ISI will not affect the probability of successful retrieval. This assertion is based upon the principle of temporal discriminability (e.g., Baddeley, 1976; Neath, 1993), in which the probability of successfully cuing a specific episode in LTM is seen to be determined by that episode’s distinctiveness in time. That is, along the dimension of time (cf. Brown et al., 2007), an episode that is relatively isolated from other events will be more readily cued than one that was relatively compressed with other events.

Key to this concept is “relative” isolation. Examining Figure 1, while the between-subjects ISIs and ITIs are different in terms of absolute time, relative time is actually constant (Baddeley, 1976; Capaldi & Neath, 1995; Neath, 1998). Regardless of the number of milliseconds contained in either interval, the ratio of ITI to ISI is fixed at 1. In both conditions, events are uniform. Thus, a lack of time-based decay can also be understood as the result of neither condition creating a situation in which target information is relatively compressed with irrelevant information. So long as the ratio of ITI to ISI is held constant within an experimental session, relative distinctiveness of any given event should not be determined by the ISI (cf. Neill et al., 1992; Turvey, Brick, & Osborne, 1970).[2]

Thus, maintenance and retrieval make the same prediction: Relative to an ITI/ISI of 900 ms, an ITI/ISI of 3,900 ms will not be associated with decayed memory of the critical array. Subsequent experiments were therefore designed to converge on a result that is consistent with only one explanation. This was accomplished by manipulating temporal discriminability. Both ITI and ISI were varied within-subjects and within-trial.

Figure 2 displays the combinations of ITI/ISI that were utilized in the other three experiments. Under these circumstances, and with regard to retrieval, two simple predictions can be made. First, if retrieval processes are critical to visual arrays performance, then the length of the ISI will influence memory for the most recent array. Unlike Experiment 1, the relative spacing of events is no longer uniform. Thus, if visual arrays performance involves recollection of information from the most recent array (rather than strict maintenance), the effects of proactive interference will fluctuate on a trial-by-trial basis. Compare (*c*) – (*a*) and (*b*) – (*d*) in Figure 2. From the perspective of the box marked “Probe Array” (i.e., attempting to look backward in time), decreasing the ISI should facilitate recollection of the “Target Array” by improving temporal proximity, thus allowing the relevant time period to be cued with greater fidelity (e.g., Glenberg & Swanson, 1986). As ISI decreases, the estimate of “WM capacity” (k) should increase.

The second prediction that pertains to retrieval from LTM regards the effect of manipulating the ITI. Increasing the length of the ITI should have an effect that is opposite of increasing the ISI. That is, a long ITI will push the “Previous Probe” array farther back in time, thus releasing the test-taker from proactive interference (Kincaid & Wickens, 1970). In terms of relative time, this effect is made apparent by viewing (*a*) – (*d*) and (*c*) – (*b*). Therefore, as ITI increases, k should also increase.

Critical to the present experiments, manipulations of temporal discriminability specifically affect retrieval processes by increasing or decreasing the intensity of proactive interference (Baddeley, 1976; Capaldi & Neath, 1995). Storage-based accounts of WM

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[2] Information regarding formal models of temporal distinctiveness can be found in Brown et al. (2007) and Neath (1993, 1998).

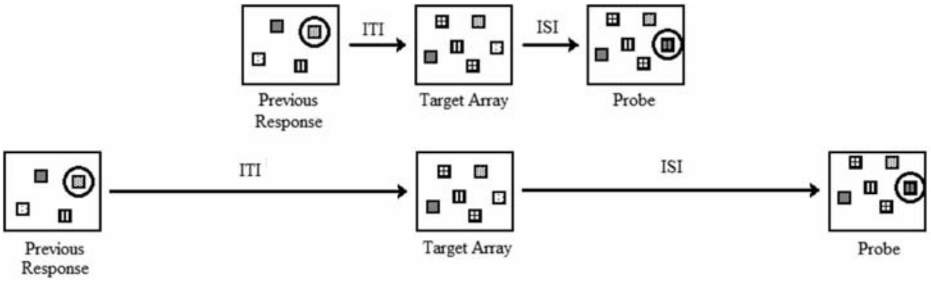

Figure 1. Between-subjects conditions in Experiment 1. ITI = inter-trial interval; ISI = inter-stimulus interval.

capacity (e.g., Awh et al., 2007; Cowan et al., 2005; Rouder et al., 2011) would have difficulty explaining the predicted fluctuations. In particular, these theories specifically assume WM is used to maintain a fixed number of items in an interference-free state (e.g., Cowan, 2001; Cowan et al., 2005). Slot-based interpretations (e.g., Rouder et al., 2011) of the relationship between WM and visual arrays performance thus predict a null effect of ISI and ITI. This is because proactive interference is not assumed to affect performance: The assumed role of WM-storage is to neutralize interference. Therefore, maintenance-based accounts, which view visual arrays performance as an indicator of a person's capacity for interference-free maintenance (e.g., Cowan et al., 2005), assume that the relative lengths of ISI and ITI are irrelevant and, thus, predict that subsequent experiments will replicate Experiment 1.

Experiment 1

Method

Participants. Sixty-one undergraduate students (40 females; mean age = 20 years) were recruited from the Georgia Institute of Technology subject pool. Participants were compensated with 1 hr of credit toward course requirements. Data were excluded for one participant who fell asleep during the session.

Materials. Participants sat roughly 45 cm from the monitor. From this distance, each square subtends 0.76° of visual angle, left to right and top to bottom (6 mm). Although square locations were randomly assigned on a trial-by-trial basis, each square was presented at a distance of more than 2° (center to center) from the next closest square. Squares locations were all at least 2° from fixation. Each square was also randomly assigned (with replacement) one of seven colors using standard E-prime color values (RGB): white (255, 255, 255), black (0, 0, 0), red (255, 0, 0), yellow (255, 255, 0), green (0, 128, 0), blue (0, 0, 255), or purple (128, 0, 128). Squares were presented within a centered silver (192, 192, 192) background (19.1° × 14.3°).

Design. Experiment 1 was a 3 (array size: 4, 6, 8) × 2 (interval length: 900 ms or 3,900 ms) design. Array sizes were manipulated within-subjects. Interval length was manipulated between-subjects. The experimenter assigned participants to interval-length condition according to a pre-randomized list.

The dependent variable was a participant's k as described by Equation A.6 of Cowan et al. (2005): $k = N \times (\text{H} + \text{CR} - 1)$. "$N$"

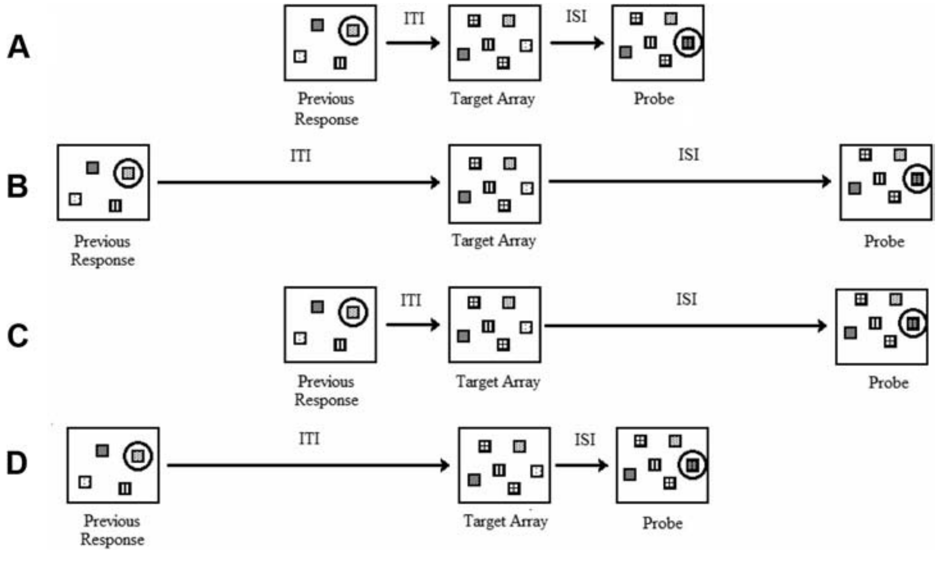

Figure 2. Within-subjects conditions used in Experiments 2–4. ITI = inter-trial interval; ISI = inter-stimulus interval.

is the array size. "H" refers to hits, or accurately recognizing that a block color has changed. "CR" refers to correct rejections, or accurately noticing that a color-change has not occurred.

We controlled for the size of the array on the previous trial, such that each array size (4, 6, 8) was preceded by each array size an equal number of times. We also controlled for the number of times a critical array size was preceded by a change or no-change trial. These variables did not enter into our formal predictions but were controlled out of concern for standardizing the histories of individual participants.

Procedure. Participants were run in a large room in groups of 1–5. Each worked at an individual computer. The experimenter remained in the room throughout the session, which lasted less than 1 hr. All studies were one session.

In order to control temporal factors, a new trial began immediately after a preceding trial response. Following an ITI (detailed below), a set of randomly arranged color squares was presented for 250 ms. The offset of this array was followed by an ISI that was of a duration equivalent to the ITI. Finally, the array reappeared with one square encircled. The participant simply judged whether this square was the same or a different color relative to its initial presentation. Judgments were made via keys labeled "S" for same and "D" for different (respectively, "f" and "j" on a standard keyboard). Participants were allowed unlimited time to respond. Thus, the critical temporal manipulation regarded (1) the space of time between the offset of the previous array and onset of the critical array and (2) the space of time between the offset of the critical array and onset of the critical response set.

Each ITI began with a white screen that lasted for 300 ms or 3,300 ms, depending upon condition (i.e., short or long interval). This was followed by a black fixation cross against a silver background that lasted for 500 ms. After a 100-ms pause, the array set was displayed. Thus, regardless of whether the total ITI was 900 ms or 3,900 ms, the signal to prepare for an array was the same in both conditions. A blank, silver screen was shown during the ISI.

In order to maintain control over events that preceded a critical array, every other trial was actually a filler trial ("Previous Response" in Figures 1 and 2). Performance on these trials was not examined, as their purpose was to ensure that each array size was preceded by an array of each size an equal number of times. Each block therefore consisted of 36 pairs of filler/critical trials, in which participants saw each potential combination of array size and previous-array size four times. Within these trials, "change" and "no change" arrays occurred an equal number of times for both the critical and previous array. In the course of an experimental session, participants completed three blocks, with self-paced rest breaks in between. Sessions began with six practice trials.

Results

Any violations of the sphericity assumption were corrected using the Huynh–Feldt procedure. Table 1 presents *k* arranged by array size and interval length. Consistent with previous studies (cf. Rouder et al., 2011), *k* increased across set sizes. *k* did not statistically differ ($p = .771$) for array sizes 6 ($k = 4.32$) and 8 ($k = 4.52$), but both of these array sizes were different from array size 4 ($k = 3.47$; both ps $< .001$). Additionally, *k* was larger for the 3,900-ms condition, relative to the 900-ms condition (respectively, 4.38 and 3.83).

Table 1
k Values at Each ISI and Array Size

ITI/ISI	Array size 4	 6	 8
□ → □ → □	3.32 (0.10)	4.00 (0.20)	4.16 (0.24)
□ → → → □ → → → □	3.63 (0.10)	4.64 (0.20)	4.87 (0.24)

Note. Standard errors of the mean are in parentheses. ITI = inter-trial interval; ISI = inter-stimulus interval.

These statements are supported by main effects of array size, $F(1.82, 105.73) = 25.86$, $MSE = 20.28$, $p < .001$, $\eta_p^2 = .31$, and interval length, $F(1, 58) = 7.61$, $MSE = 13.89$, $p < .01$, $\eta_p^2 = .12$. The interaction of array size and internal-length did not approach significance, $F(2, 116) = 0.96$, $MSE = 0.689$, $p = .39$, $\eta_p^2 = .02$.

Discussion

Experiment 1 was conducted with the explicit intention of demonstrating that memory for an array does not decay over the course of 4 s (e.g., Vogel et al., 2001). Consistent with our predictions, *k* did not shrink over time. In fact, the long-interval group had a statistically larger *k* than did the short-interval group. One might assume that this difference is a byproduct of the between-subjects design. That is, perhaps the 3,900-ms group had a larger WM capacity than the 900-ms group. We note that due to (1) the use of a large sample ($n = 60$), along with (2) random assignment and (3) a sample that was likely composed of a fairly homogenous sample of people with higher than average WM capacity (i.e., all Georgia Institute of Technology students; see Redick et al., in press), this interpretation is unlikely. We explore the potential meaningfulness of this finding in the General Discussion.

Experiment 2

Method

Participants. Thirty-two undergraduate students (14 females, 17 males;[3] mean age = 19.7 years) were recruited from the Georgia Institute of Technology subject pool. None had participated in Experiment 1. Participants were compensated with 1 hr of credit toward course requirements.

Design. All variables in Experiment 2 were manipulated within-subjects. The design was 3 (array size: 4, 6, 8) × 2 (ITI length: 900 ms vs. 3,900 ms) × 2 (ISI length: 900 ms vs. 3,900 ms). The dependent variable was not changed.

Procedure. Experiment 2 was similar to Experiment 1, with the exception that ITI and ISI were no longer fixed. Four possible combinations of ITI/ISI occurred within a single session (see Figure 2). These combinations included 900/900; 3,900/3,900; 900/3,900; 3,900/900.

As with the first experiment, the "Previous Response" (see Figure 2) was made in a filler trial that controlled previous array

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[3] Demographic information for one participant was lost.

size and previous response. Due to time constraints, the ITI/ISI for filler trials was always 900/900.[4] As with the first experiment, participants received each combination of array size and previous array size; however, these were also presented within each potential combination of ITI/ISI four times per block. Each block included 144 trials. Participants completed two blocks in each session, with a self-paced break in between each. Each session began with eight practice trials in which participants encountered each potential combination of ITI/ISI two times.

Results

As predicted, the effects of manipulating the ISI and ITI were both significant. Decreasing the ISI (thus making the to-be-remembered array temporally proximate) was associated with a significant increase in k (2.79 when ISI = 3,900 ms; 3.55 when ISI = 900 ms). Conversely, increasing the ITI (and thus temporally separating the previous response screen and the critical array) was associated with an increase in k (2.96 when ITI = 900 ms; 3.39 when ITI = 3,900 ms).

As with the first experiment, there was a main effect of array size, such that participants had a larger k when array size was 6, relative to when array size was 4 (respectively, 3.40 and 2.88; p = .001). However, neither differed from array size 8 (3.22; respective ps = .91 and .40).

Table 2 reveals that increased ISI was associated with decreased k for all array sizes. The effect was apparent at array size 4 ($\Delta k = 0.34$; $p = .003$) and grew for array sizes 6 ($\Delta k = 0.59$; $p = .005$) and 8 ($\Delta k = 1.37$; $p < .001$). This interpretation is supported by within-subjects contrasts that revealed the interaction as linear, $F(1, 31) = 17.15$, $MSE = 50.53$, $p < .001$.

The above statements are supported by main effects of ISI, $F(1, 31) = 64.86$, $MSE = 55.89$, $p < .001$, $\eta_p^2 = .68$; ITI, $F(1, 31) = 15.28$, $MSE = 17.868$, $p < .001$, $\eta_p^2 = .33$; and array size, $F(1.58, 48.84) = 4.39$, $MSE = 11.08$, $p < .03$, $\eta_p^2 = .12$. Additionally, the interaction of ISI and array size was significant, $F(2, 62) = 8.48$, $MSE = 9.175$, $p = .001$, $\eta_p^2 = .22$. An interaction of array size by ITI approached but did not reach significance, $F(2, 62) = 2.60$, $MSE = 2.05$, $p < .09$, $\eta_p^2 = .08$. No other interactions approached significance (all ps > .12; all η_p^2s < .07).

Discussion

The critical predictions regarding the influence of proactive interference on visual arrays performance were confirmed. When ISI was increased from 900 ms to 3,900 ms, participants' k values shrank. Taken in conjunction with Experiment 1, and consistent with previous research (e.g., Neill et al., 1992; Turvey et al., 1970), this effect cannot be attributed to time-based decay: It was only present when the ratio of ITI to ISI varied on a trial-by-trial basis.

Table 2
Effects of ITI and ISI at Each Array Size

	Array size		
ITI/ISI	4	6	8
□ → □	3.06 (0.13)	3.70 (0.22)	3.91 (0.32)
□ → → → □	2.72 (0.15)	3.11 (0.22)	2.54 (0.33)
□ → □	2.80 (0.15)	3.18 (0.22)	2.89 (0.30)
□ → → → □	2.97 (0.13)	3.63 (0.22)	3.56 (0.35)

Note. Standard errors of the mean are in parentheses. ITI = inter-trial interval; ISI = inter-stimulus interval.

Experiment 3

The results of the second experiment are inconsistent with the hypothesis that performance on the visual arrays task purely reflects fixed-capacity storage. However, the array sizes used in Experiment 2 were all at or above the supposed storage capacity of WM. Thus, changes in k that accompany fluctuations in retrieval difficulty may reflect retrieval from outside of a 2–3 item storage system. Experiment 3 addressed this issue by using array sizes of 2, 3, and 4. A 2–3 item account predicts that effects such as those found in Experiment 2 will be apparent at array size 4, but completely absent from array size 2, which should easily be stored in WM.

Method

Participants. Thirty-one undergraduate students (16 females; mean age = 19.7 years[5]) were recruited from the Georgia Institute of Technology subject pool. None had participated in the previous experiments. Participants were compensated with 1 hr of credit toward course requirements.

Design and procedure. The only difference between Experiments 2 and 3 is that Experiment 3 used array set sizes of 2, 3, and 4.

Results

General analysis. The main effects of array size, $F(1.75, 52.61) = 202.22$, $MSE = 72.69$, $p < .001$, $\eta_p^2 = .87$; ISI, $F(1, 30) = 16.41$, $MSE = 5.40$, $p < .001$, $\eta_p^2 = .35$; ITI, $F(1, 30) = 8.18$, $MSE = 0.67$, $p = .008$, $\eta_p^2 = .21$; and the Array Size × ISI interaction, $F(2, 60) = 3.22$, $MSE = 0.43$, $p < .05$, $\eta_p^2 = .05$, that were found in Experiment 2 replicated in Experiment 3. The only other interaction to approach significance was Array Size × ISI × ITI, $F(2, 60) = 2.96$, $MSE = 0.28$, $p = .06$, $\eta_p^2 = .09$ (all other ps > .3, η_p^2s < .04).

However, across conditions the average k value was 2.26 (see Table 3), which is larger than possible k values in the smallest array size condition (i.e., 2 items) and smaller than the k usually found when array size is 4 (i.e., 3–4 items). Therefore, the results are presented as a series of 2 × 2 analyses of variance (ANOVAs) at each set size.

Array size 2. The overall k value when array size was 2 was 1.56. k was larger when the ISI was 900 ms (1.61) relative to when it was 3,900 ms (1.50). Additionally, k was smaller when the ITI

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[4] Our initial justification for using short intervals on buffer trials was based on the argument that temporal distinctiveness is affected by all trials leading to the present trial (Cowan et al., 2001). Thus, the effect of a long ISI would be increased. However, Pierre Barrouillet (personal communication, June 1, 2011) noted that, because long ISIs were unusual, participants may have engaged in encoding strategies that were amenable to short ISIs. We note that the main effect of ISI replicates in Experiment 4, in which long and short intervals were equally probable.

[5] This is based on 30 participants, as one filled in her name rather than age.

Table 3
Effects of ITI and ISI at Each Array Size

ITI/ISI	Array size 2	Array size 3	Array size 4
□ → □	1.61 (0.07)	2.36 (0.10)	3.16 (0.13)
□ → → → □	1.50 (0.09)	2.09 (0.12)	2.82 (0.18)
□ → □	1.50 (0.08)	2.15 (0.11)	3.00 (0.15)
□ → → → □	1.61 (0.08)	2.30 (0.11)	2.98 (0.16)

Note. Standard errors of the mean are in parentheses. ITI = inter-trial interval; ISI = inter-stimulus interval.

was 900 ms (1.50) relative to when it was 3,900 ms (1.61). Although these changes were numerically small, they were reliable, as revealed by main effects of both ISI, $F(1, 30) = 7.65$, $MSE = 0.40$, $p = .01$, $\eta_p^2 = .20$, and ITI, $F(1, 30) = 7.51$, $MSE = 0.40$, $p = .01$, $\eta_p^2 = .20$. These two variables did not interact ($p = .45$, $\eta_p^2 = .02$).

Array size 3. When array size was 3, the overall *k* value was 2.23. Once again, *k* was larger when ISI was 900 ms (2.36) relative to when it was 3,900 ms (2.01), and *k* was smaller when ITI was 900 ms (2.15) relative to when it was 3,900 ms (2.30). These observations are supported by main effects of ISI, $F(1, 30) = 10.71$, $MSE = 2.20$, $p = .003$, $\eta_p^2 = .26$, and ITI, $F(1, 30) = 4.80$, $MSE = 0.728$, $p = .04$, $\eta_p^2 = .14$.

These effects, however, are qualified by a significant ISI × ITI interaction, $F(1, 30) = 7.12$, $MSE = 0.653$, $p = .01$, $\eta_p^2 = .19$. When ISI was 900 ms, the length of the ITI did not have a numerical effect on *k* (2.36 in both cases). However, when ISI was 3,900 ms, ITI did have an effect on *k* ($k = 1.94$ when ITI was 900 ms, $k = 2.24$ when ITI was 3,900 ms; $p = .004$). From the perspective of ITI, the effect of ISI was reliable when ITI was 900 ms (ISI = 900 ms, $k = 2.36$; ISI = 3,900 ms, $k = 1.94$; $p = .001$) but was not reliable when ITI was 3,900 ms (ISI = 900 ms, $k = 2.36$; ISI = 3,900 ms, $k = 2.24$; $p = .12$).

Array size 4. A main effect of ISI, $F(1, 30) = 10.83$, $MSE = 3.67$, $p = .003$, $\eta_p^2 = .27$, revealed that, as in the other conditions, *k* was larger when ISI was 900 ms (3.16) than it was when ISI was 3,900 ms (2.81). However, no effect of ITI was found, and ITI did not interact with ISI (both ps $> .88$, η_p^2s $< .002$).

Discussion

Experiment 3 demonstrates that the effects found in Experiment 2 are apparent even with array sizes as small as two items. The effect of ITI weakened as set size increased from two to four items. Although this is curious, we note that the direction of the trend is opposite to what would be predicted by a WM storage model. That is, the effect should have shrank as set size decreased.

It might be assumed that the smaller set sizes (i.e., two and three items) created less proactive interference and thus increased the relative distinctiveness of four item sets (e.g., Lustig, May, & Hasher, 2001). We explored this possibility by conducting a post hoc analysis of four-item arrays as a function of previous set size. Neither an effect of previous array size nor an interaction of previous array size with ITI was obtained (all ps $> .5$, η_p^2s $< .02$).

Experiment 3 is not a clean replication of Experiment 2, but this is understandable. Whereas Experiment 2 focused on memory sets that were larger than the average person's *k*, Experiment 3 focused memory sets that were sub-*k*. Thus, despite a disappearing effect of ITI as set size increased, the important finding of Experiment 3 is that ISI and ITI effects are apparent even for sets of items that should readily be stored in WM.

Experiment 4

Although the experiments have thus far demonstrated that *k* is subject to retrieval-related effects, one may question whether these effects are meaningful. Is *k* more predictive of cognitive ability under certain temporal conditions, or is its predictive power fixed across all conditions?

Storage-based accounts of WM capacity assume that the relationship between visual arrays performance and Gf (i.e., novel problem solving) is based on the number of units of information a person can store in WM at any one point in time (Cowan, 2001; Fukuda et al., 2010). Although the results of Experiments 3 are incompatible with the assumption of fixed-capacity WM storage at any size, the predictive power of *k* may remain more-or-less constant across manipulations of temporal discriminability. That is, stable differences in the size of *k*, regardless of fluctuations of proactive interference, may be the factor that links visual arrays performance to cognitive ability, rather than the ability to manage proactive interference within a given context.

This view contrasts Unsworth and Engle's (2007) proposal that low WM capacity is associated with difficulty constraining searches of LTM to specific periods of time. By this account, visual arrays performance will be most strongly related to WM capacity when temporal discriminability is at its lowest (i.e., long ISI and short ITI). In other words, WM capacity (as measured by complex span tasks) will be most strongly correlated to visual arrays under conditions that reduce the size of *k* and will be most weakly correlated in situations that increase the size of *k*. Further, Unsworth and Engle assumed that individual differences in temporal-contextual retrieval are largely (but not entirely) responsible for the relationship between Gf and measures of WM capacity. Thus, this theory predicts that Gf will correlate to visual arrays in a manner that replicates complex span.

To preview the results of Experiment 4, the predictions of Unsworth and Engle (2007) were supported, but only as they relate to WM capacity. To our surprise, *k* was a better predictor of Gf when the ITI was long, rather than short. We thus ultimately argue that the results of Experiment 4 favor perspectives of WM capacity that include a component of *updating* or *forgetting* of no-longer-relevant information (i.e., Miyake et al., 2000; Oberauer et al., 2007; Wiley et al., 2011).

Method

Participants. In order to increase the cognitive diversity of our sample, 54 participants (31 females; mean age = 23.8 years) were recruited from our prescreened subject pool of college students (e.g., Georgia Institute of Technology, Georgia State) and members of the general Atlanta community. Participants were reimbursed with $20 for their participation. Data for one participant, who did not follow instructions, were not examined.

Design and procedure. The visual arrays task in Experiment 4 was similar to the one from Experiment 2. However, in an attempt to create a less contrived context, buffer trials were removed. This meant that "Previous Response" was now the response from the previous probe array. As such, previous response type, previous set size, and the ITI/ISI of the preceding trial were free to vary. Thus, unlike Experiments 2 and 3, ITI/ISI of 900/900 was no longer the dominant trial type.

Experiment 4 included two blocks of trials separated by a self-paced rest break. Within each block, participants responded to each array size under each ITI/ISI combination twice as a change-trial and twice as a no-change trial. The first trial of each block was not preceded by an array and thus was dropped from further analysis.[6] Each session, therefore, included 98 trials and lasted approximately 45 min. Participants were run in groups of one to five.

All participants had been prescreened on two complex span tasks and three Gf tasks. Scores on the complex span and Gf tasks were combined into respective *z* scores referred to as "WM-span" and "Gf."

Complex span tasks. Complex span tasks require test-takers to remember a series of items while performing interpolated processing tasks. After 2–7 items are presented, the participant is signaled to recreate the list in it proper serial order. The complex span tasks used in this study may be downloaded at http://psychology.gatech.edu/renglelab/.

The operation span (ospan; Unsworth, Heitz, Schrock, & Engle, 2005) requires test-takers to remember a list of letters. In between the presentation of each letter, a simple mathematical equation must be solved. Lists contained 3–7 items, and each list length appeared three times.

The symmetry span (symmspan; Unsworth, Redick, Heitz, Broadway, & Engle, 2009) task requires test-takers to remember a series of spatial locations presented in a 4 × 4 grid served. In between the presentation of each item, participants are shown a black and white figure on an 8 × 8 grid. They were required to indicate whether or not the figure was symmetrical. List contained 2–5 items, and each list length appeared three times.

General fluid intelligence. All fluid intelligence tasks were administered via computer. Participants provided answers via mouse click.

Raven's Advanced Progressive Matrices (RAPM; Raven, 1990) requires test-takers to choose which of several options completes a series of eight abstract objects. The objects are arranged in a 3 × 3 matrix with a blank space in the final location. Test-takers were allowed 10 min to complete 18 problems (odd set).

Letter sets (Ekstrom, French, Harman, & Dermen, 1976) display five groups of four letters and require test-takers to discover a rule that is common to four the groups. Thus, the requirement of this task is to indicate which set violates the rule. A total of 5 min was given to complete 20 problems.

Number series (Thurstone, 1938) displays a series of numbers, and test-takers select which of several options completed the series. A total of 4.5 min was given to complete 15 problems.

Results

Visual arrays. Mean *k* was 3.53. Between array sizes, *k* increased from 3.26 at set size 4 to 3.77 at set size 6 ($p < .001$). *k* at set size 8 (3.56) did not differ from the other values ($p > .25$).

Table 4
Effects of ITI and ISI

	Array size		
ITI/ISI	4	6	8
□ → □	3.38 (0.10)	3.96 (0.19)	3.87 (0.25)
□ → → → □	3.15 (0.12)	3.59 (0.19)	3.25 (0.23)
□ → □	3.21 (0.11)	3.67 (0.19)	3.21 (0.24)
□ → → → □	3.31 (0.11)	3.88 (0.21)	3.88 (0.23)

Note. Standard errors of the mean are in parentheses. ITI = inter-trial interval; ISI = inter-stimulus interval.

Table 4 indicates that *k* decreased when ISI was extended from 900 ms (3.74) to 3,900 ms (3.33) and increased when ITI was extended from 900 ms (3.37) to 3,900 ms (3.69). These observations are supported by main effects of array size, $F(1.76, 91.63) = 6.31$, $MSE = 16.07$, $p = .004$, $\eta_p^2 = .11$; ISI, $F(1, 52) = 15.13$, $MSE = 26.55$, $p < .001$, $\eta_p^2 = .23$; and ITI, $F(1, 52) = 9.74$, $MSE = 16.35$, $p = .003$, $\eta_p^2 = .16$.

The only interaction to approach significance was that of Array Size × ITI, $F(2, 104) = 2.72$, $MSE = 4.64$, $p > .07$, $\eta_p^2 = .05$. This trend suggests that the effect of ITI increased from array sizes 4–8 (.11, .21, .67). This interpretation is supported by a significant linear within-subjects contrast, $F(1, 52) = 4.46$, $MSE = 8.28$, $p < .05$, $\eta_p^2 = .08$. No other interactions approached significance (all $ps > .19$, $\eta_p^2 s < .04$).

Correlation to WM-span and Gf. The correlations between *k* and WM-span and *k* and Gf for each combination of ISI and ITI are displayed in Table 5 (the full correlation matrix can be found in the Appendix). First, examining the correlation between *k* and WM-span, the overall effect of extending ISI numerically strengthened this relationship from .33 to .46. However, a two-tailed dependent correlation analysis (Cohen & Cohen, 1983) revealed that this change was not reliable ($t = 1.53$; $p = .13$). The overall effect of extending ITI numerically weakened this relationship from .45 to .35. This change was not reliable either ($t = 1.19$; $p = .24$).

The individual combinations of ISI and ITI in Table 6 reveal that the relationship between *k* and WM-span is not driven by the absolute length of ISI or ITI but rather by overall temporal discriminability. When ISI and ITI are of equal length, the correlation to WM-span is similar regardless of whether that length is 900 ms ($r = .32$) or 3,900 ms ($r = .35$; $t = .27$; $p = .79$). However, the correlation weakens from .51 when temporal discriminability is low (ITI = 900/ISI = 3,900) to .29 when temporal discriminability is high (ITI = 3,900/ISI = 900; $t = –2.07$; $p < .05$).

Returning to Table 5, the correlation between *k* and Gf strengthened from .43 to .59 when ISI was increased ($t = 2.21$; $p < .04$). Similarly, the overall effect of extending the ITI strengthened this relationship from .42 to .59 ($t = 2.25$; $p = .03$).

As with WM-span, the relationship between *k* and Gf is not straightforward. Table 6 reveals that, unlike WM-span, the relationship of *k* to Gf was stable across conditions of low (.45) and high (.47) temporal discriminability ($t = 0.19$; $p = .85$). On the

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[6] This was due to a programming oversight. Inclusion of these two trials does not change the results.

Table 5
Effects of ITI and ISI on the Correlations Between k and WM-Span and Gf

ITI/ISI	*k*	*r*WM-span	*r*Gf
□ → □	3.74 (0.16)	.33	.43
□ → → → □	3.33 (0.15)	.46	.59
□ → □	3.37 (0.15)	.45	.42
□ → → → □	3.69 (0.16)	.35	.59

Note. Standard errors of the mean are in parentheses. All correlations are significant at $p < .05$. ITI = inter-trial interval; ISI = inter-stimulus interval; WM-span = working memory span; Gf = general fluid intelligence.

other hand, when ISI and ITI were of equal length, the correlation between *k* and Gf strengthened as the interval length increased from 900 ms (.33) to 3,900 ms (.61; $t = 2.94$; $p = .005$).

Discussion

Experiment 4 demonstrates that the manipulations thus far employed are meaningful to the prediction of WM-span and Gf. In particular, the correlation between visual arrays and WM-span was most affected by extreme manipulations of temporal discriminability, which is consistent with Unsworth and Engle's (2007) assumption that WM capacity largely reflects individual differences in the ability to conduct temporal-contextual searches of memory. In a standard visual arrays task, this would be most apparent after several trials have been run and proactive interference is in place (e.g., Bunting, 2006; Lustig et al., 2001).

The relationship of Gf to visual arrays performance stands in contrast to that of WM-span and visual arrays. Whereas the correlation between WM-span and visual arrays was mainly influenced by the overall temporal discriminability of a trial, the correlation between Gf and visual arrays was more sensitive to the individual lengths of the ISI and ITI. Surprisingly, the correlation between Gf and visual arrays was stronger when the ITI was long, rather than when it was short.

We interpret the latter phenomenon as an instance of individual differences in memory "updating" (e.g., Miyake et al., 2000; Oberauer et al., 2007; Wiley et al., 2011). This interpretation is predicated upon two assumptions. First, individual differences in updating are not always fully realized at short intervals, but they can become apparent over time. Second, it is the context used for retrieval (e.g., bindings) that is "updated," rather than information that is maintained within a WM store.

Table 6
Correlation Between k and WM-Span and Gf at Separate Levels of Discriminability

ITI/ISI	*k*	*r*WM-span	*r*Gf
□ → □ → □	3.58 (0.16)	.32	.33
□ → → → □ → → → □	3.50 (0.18)	.35	.61
□ → □ → → → □	3.16 (0.16)	.51	.45
□ → → → □ → □	3.89 (0.18)	.29	.47

Note. Standard errors of the mean are in parentheses. All correlations are significant at $p < .05$. WM-span = working memory span; Gf = general fluid intelligence; ITI = inter-trial interval; ISI = inter-stimulus interval.

Table 7
Effect of ITI on k at Three Levels of Gf

	Gf					
ITI	Low ($n = 17$)		Mid ($n = 18$)		High ($n = 18$)	
900	3.10	$p = .50$	3.39	$p = .13$	3.60	$p = .002$
3,900	3.22		3.64		4.18	

Note. Standard errors of the mean are in parentheses. All correlations are significant at $p < .05$. ITI = inter-trial interval; Gf = general fluid intelligence.

The first point is clarified by examining the data from the perspective of ITI and Gf. Table 7 indicates that the longer ITI was specifically beneficial to individuals with high Gf, as their *k* values increased by about half an item. Low Gf individuals, on the other hand, did not benefit from the increased ITI. This trend is consistent with the proposal that people with low Gf are susceptible to perseveration of no-longer-relevant information in WM (e.g., Wiley et al., 2011), which ultimately prevents them from generating novel solutions to problems. Conversely, though it may require time, high Gf individuals are capable of disengaging from no-longer-relevant information, thus allowing for better memory of relevant information.

The second point states that updating is not performed on an interference-free multi-item store. Although the concept of updating a WM store is intuitively concrete (and therefore appealing), it must contend with the results of Experiment 3, which found interference effects using array sizes of only two items. Thus, while we are cautious in our endorsement of a concept as abstract as "binding," we note that the data imply that updating is performed on the context used during a retrieval attempt, rather than on stored information.

It may alternately be argued that high Gf individuals experience a more rapid decay of no-longer-relevant information than do low Gf individuals. Though Experiment 4 is not inconsistent with this explanation, the concept of decay over absolute time has a rocky past as a causal mechanism (e.g., Capaldi & Neath, 1995; Keppel & Underwood, 1962; Lewandowsky, Oberauer, & Brown, 2009; Nairne, 2002). Moreover, controlled processes are known to require absolute time to engage (e.g., Neely, 1977), and their ultimate efficacy over time is subject to individual differences (e.g., Balota, Black, & Cheney, 1992; Heitz & Engle, 2007; Hutchison, 2007). Regardless of explanation (updating or decay of irrelevant information), Experiment 4 demonstrates that (1) the predictive power of *k* is not fixed and (2) not all people have the same reaction to proactive interference that is generated during a visual arrays task.

General Discussion

Trials in the visual arrays task are events along the continuum of time (e.g., Brown et al., 2007; Crowder, 1976) and therefore generate proactive interference. Traditional interpretations of visual array performance assume that this interference is counteracted by a fixed-capacity component of WM. However, across four experiments, we found little evidence for such a storage system. Rather, interference effects are apparent across a variety of array sizes. Moreover, the relationship of *k* to WM-span and Gf tasks is not driven by the absolute size of *k* (see Table 6) but rather is driven by the ability of an individual to manage interference within certain sets of conditions.

The finding of that high Gf individuals are particularly sensitive to long ITIs (Experiment 4) suggests that the increased *k* over time seen in Experiment 1 may represent an interaction of balanced temporal circumstances along with a high-ability sample (e.g., Georgia Institute of Technology students; see Redick et al., in press). That is, if high Gf individuals are indeed capable of using longer ITIs to engage in intentional forgetting of no-longer-relevant information, their memory will improve as absolute interval length increases, provided the ratio of ITI to ISI remains at 1. It also suggests that this effect is subject to individual differences.

We interpret our data as being most readily reconciled within Oberauer's (2002; Oberauer et al., 2007) concentric model of WM, in which a region of direct access is formed through contextual bindings between units of activated LTM and a single-item focus of attention. However, this study does not provide evidence supporting the existence a single-item focus of attention. Rather, within the context of the visual arrays task, it provides evidence against a multi-item focus of attention. This distinction is particularly relevant given the recent theoretical concession by Oberauer and Bialkova (2011) that the single-item focus of attention is not a structurally fixed feature of WM but rather is a type of processing that is used to reduce cross-talk in novel situations.

Release From Proactive Interference

The present studies focus on time-based release from proactive interference (Kincaid & Wickens, 1970), rather than release from proactive interference in response to a change of category (Wickens et al., 1963). Indeed, both are deemed to be important sources of context around which memory is organized (e.g., Polyn, Norman, & Kahana, 2009a, 2009b). As such, one would expect visual arrays to be subject to both types of release from proactive interference.

However, as referenced in the introduction, studies involving categorical release from proactive interference have produced equivocal results. Although Hartshorne (2008) found evidence for such release, Lin and Luck (2012) did not when they used short presentation times (100 ms) and short retention intervals (900 ms). These researchers thus argued that LTM will only affect visual arrays performance when longer time intervals are used.

Although Lin and Luck (2012) did not prescribe an interval at which the influence of LTM becomes apparent, it might be argued that our 250-ms array presentation allowed time for such processes to engage. This interpretation is contradicted by the results of Experiment 1, in which no evidence of increased interference over longer intervals was found. Instead, we interpret an interesting discrepancy between the methods of Hartshorne (2008) and Lin and Luck (2012) within the context of the present results.

Hartshorne's (2008) second experiment found release from proactive interference, using arrays that were presented for 1,000 ms followed by a 1,000-ms retention interval. Lin and Luck (2012) presented arrays for 100 ms, followed by a 900-ms retention interval. This was not the only difference between these studies. Hartshorne reported that each trial began with a 500-ms fixation. Lin and Luck, on the other hand, ended each trial with an ITI of 1,000 ms, followed by a separate fixation period of 1,000 ms. Thus, end-to-beginning, the trials in Hartshorne were compressed in time, whereas the short trials of Lin and Luck were relatively isolated. This provides an alternate explanation of the null effect found by Lin and Luck: Rather than decreasing the role of LTM by making the trials shorter, they may have reduced the meaningfulness of the category change by isolating each target array in time.

Alternate Accounts and Limitations

The effect of ITI. It has been suggested to us that the effect of ITI may represent the effect of being given extra time to prepare for the next trial. To the extent that this explanation can be conflated with the individual differences variable that we have termed "updating," we are inclined to agree. However, the results of Experiment 4 reveal that people are sensitive to ITI changes in more than one way. Specifically, while Gf most strongly relates to *k* when ITI-related discriminability is high, the correlation between WM-span and *k* specifically strengthens in response to low temporal discriminability.

It would be parsimonious to argue that both of these effects are preparation: WM-span representing rapid updating and Gf representing a slower process. However, this explanation must contend with the finding that WM-span was not always sensitive to the length of ITI. Instead, WM-span is most important when a short ITI is paired with a long ISI (i.e., low temporal discriminability).

Verbal recoding. A second concern regards our lack of a manipulation to discourage verbal recoding of visual material. This may explain the inflated *k* scores in the long ISI condition of Experiment 1: Participants knew that they would need to retain information for an extended period and also knew that they had ample time to recode the information into an articulatory format.

Although recoding provides a viable explanation of this particular effect (i.e., increased *k* when long intervals were fixed), it does not endanger the next three experiments. In all subsequent experiments, increases and decreases in *k* followed a pattern that is consistent with temporal discriminability research (e.g., Neill et al., 1992; Turvey et al., 1970) and theory (e.g., Baddeley, 1976; Capaldi & Neath, 1995). Additionally, examination of Table 6 reveals that in Experiment 4 (in which long and short ISIs were equally probable), *k* values were not time-sensitive on trials in which the ISI and ITI were equal. Thus, while increased-*k*-over-time can be explained as an artifact of the between-subjects design, the lack-of-decay cannot.

Masked stimuli. None of our studies employed a post-perceptual mask to reduce any effects of residual sensory information (e.g., Sligate, Scholte, & Lamme, 2008) and ostensibly obtain a cleaner estimate of fixed-capacity WM (e.g., Rouder et al., 2008; Saults & Cowan, 2007). Although such an manipulation is potentially informative, we argue that its absence does not threaten the present results. Beyond the lack of absolute time-based decay found in Experiment 1 (which would have been apparent if time-limited sensory information was being used), the smaller array sizes used in Experiment 3 should have been fully stored in WM. However, even these small set sizes were subject to discriminability effects.

Characteristics of the target and probe arrays. Finally, in all experiments, colors were allowed to repeat within an array, and the probe included all items from the target array, rather than a single probe. Thus, based on the work of Wheeler and Treisman (2002), it might be argued that the color repetitions either increased difficulty of maintaining binding between color and location during the ISI, or they created interference when the whole-display probe was presented.

We had initially considered the first possibility (i.e., inter-item interference during retention) as an explanation of the Array Size × ISI interaction that was found in Experiments 2 and 3. However, this explanation is contradicted by Experiments 1 and 4, neither of which found such an effect. Thus, we attribute the Array Size × ISI interaction as evidence that larger set sizes are more sensitive to the lower global temporal discriminability (e.g., Cowan, Saults, & Nugent, 2001) in Experiments 2 and 3 that was created by the presence of 900-ms buffer trials.

It is possible that whole displays may increase interference by providing a greater number of comparisons. However, inter-item interference at response cannot explain all interference effects. Hartshorne (2008) was able to find interference using single-item probes. Moreover, our third experiment found significant effects with probe displays of two items. These displays not only minimize the potential for within-display color repetitions but also minimize competition for representation in attention.

Conclusions

The history of psychology contains many examples of effects that were once attributed to decay (e.g., Cowan, Saults, & Nugent, 1997; Neill & Westberry, 1987; Peterson & Peterson, 1959) but were later reinterpreted as proactive interference in light of new evidence (respectively: Cowan et al., 2001; Keppel & Underwood, 1962; Neill et al., 1992; see also Lewandowsky et al., 2009). The present studies take a different angle by demonstrating that proactive interference influences performance in a paradigm that is generally believed to reflect interference-free multi-item storage. These effects are numerically small (see also Hartshorne, 2008), yet we contend that their importance cannot be judged based on absolute size: They are apparent at sub-*k* array sizes and produce significant changes to the predictive nature of the task. In the end, *k* provides a simple and meaningful index of a person's working memory. However, the present results provide ample evidence that the mechanisms underlying *k* are complex and multiply-determined.

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Appendix

Correlations Among Tasks and Conditions in Experiment 4

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
ISI1	—														
ISI2	.77	—													
ITI1	.89	.88	—												
ITI2	.90	.89	.78	—											
ISI1_ITI1	.92	.73	.92	.75	—										
ISI2_ITI2	.70	.92	.70	.91	.64	—									
ISI2_ITI1	.70	.89	.92	.69	.69	.64	—								
ISI1_ITI2	.93	.70	.73	.91	.72	.66	.62	—							
WM-span	.33	.46	.45	.35	.32	.35	.51	.29	—						
Ospan	.12	.18	.24	.08	.19	.09	.25	.05	.82	—					
Symspan	.42	.58	.50	.50	.34	.48	.58	.43	.82	.35	—				
Gf	.43	.59	.42	.59	.33	.61	.45	.47	.50	.23	.59	—			
Raven	.50	.51	.39	.62	.40	.60	.31	.52	.33	.10	.45	.76	—		
LettS	.24	.40	.27	.37	.14	.37	.36	.31	.37	.20	.41	.80	.34	—	
NumbS	.30	.52	.36	.45	.24	.52	.42	.30	.50	.27	.56	.87	.50	.60	—
M	3.73	3.33	3.37	3.69	3.58	3.50	3.16	3.89	0	57.70	28.58	0	9.26	10.11	9.42
SEM	0.16	0.15	0.15	0.16	0.16	0.18	0.16	0.18	0.11	1.77	0.98	0.11	0.42	0.43	0.38

Note. All correlations above .28 are significant at the .05 level. ISI1 = inter-stimulus interval of 900 ms; ISI2 = inter-stimulus interval of 3,900 ms; ITI1 = inter-trial interval of 900 ms; ITI2 = inter-trial interval of 3,900 ms; working memory (WM)-span = a *z*-score composite of operation span (Ospan) and symmetry span (Symspan); general fluid intelligence (Gf) = a *z*-score composite of Raven's Advanced Progressive Matrices (Raven), Letter Sets (LettS), and Number Series (NumbS).

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