TEMPORAL DYNAMICS OF VISUAL SHORT-TERM MEMORIES

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ABSTRACT

Using visual displays consisting of single items to be stored in visual short-term memory (VSTM), Jacob, Breitmeyer & Treviño (2013) demonstrated three stages of information processing in VSTM: iconic visible persistence, iconic informational persistence, and visual working memory. To investigate the effect of higher memory load on these proposed VSTM stages, several measures of VSTM scanning and visual search efficiency including VSTM capacity, VSTM scanning and visual search slopes, and stimulus comparison effects, were obtained in the first part of the study, using 1, 3, and 5 display items. Results again revealed three stages of VSTM processing, but with a second phase growing longer as memory load increased, suggesting a need for a longer VSTM encoding process in this phase, and VSTM maintenance in the third stage. The second part of the study investigated whether these three stages of information processing are due to task-dependent strategic effects. Separate groups of observers were run in stimulus priming and comparison tasks using (1) a short range of SOAs exploring the first two seconds and (2) a longer range of SOAs exploring the first four seconds of post-stimulus processing. Half the trials were blocked by SOA, and in the other half SOAs were tested in a randomly intermixed order. Priming and comparison effects in the short-range experiment demonstrated, as before, three stages of post-stimulus processing in VSTM, and comparison effects in the long-range experiment showed evidence for an additional fourth stage of VSTM processing. Furthermore, in the short-range experiment, higher priming effects occurred when trials were blocked by SOA. In contrast, the priming effect across SOAs in the long-range experiment and the comparison effect in both SOA ranges were not influenced by SOA-blocked or -intermixed trials. This is indicative that the initial three stages as well as the later stages of VSTM are not an artifact of the manner in which observers are tested. These findings and their implications are related to other paradigms and methods used to investigate post-stimulus processing.

ACKNOWLEDGEMENTS

I am most thankful to my advisor, Dr. Bruno G. Breitmeyer, for his guidance and support in this work. His advice and ideas have been invaluable, and it was a privilege to be mentored by him. I am also grateful for my lab members for their help in collecting the data and their encouraging words. Their keen interest in visual cognition and dedication to the lab has made this work possible.

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DEDICATION

This work is the fruit of many prayers and is dedicated to my parents, whose fervent prayers and unchanging support have brought me thus far. Despite my formal education, I have learned the most important lesson from their life: faith can move mountains. And now, my life is a testament to this as well.

Temporal Dynamics of Visual Short-Term Memories

Visual short-term memories (VSTMs) are key components in visual information processing, allowing one to identify features of the visual objects and/or track and compare those objects to information present in working memory or long-term memory store. The traditional view holds that there are two types of VSTM. The first is a temporary sensory store, also called iconic memory, which can hold many items in memory for up to about 500 ms (Averbach & Coriell, 1961; Becker, Pashler & Anstis, 2000; Di Lollo, 1977; Sperling, 1960). The second is a post-iconic memory, a more durable visual working memory in which information remains for several seconds, but it is limited in the number of items stored (O'Herron & Von der Heydt, 2009; Zhang & Luck, 2009).

Recent work by Jacob, Breitmeyer and Treviño (2013) explored the first two seconds of post-stimulus processing using priming and comparison tasks. In both tasks, a probe stimulus followed a prime stimulus at varying stimulus onset asynchronies (SOAs); and in the priming task, participants reported the feature (color, shape) of the probe while, in the comparison task, they compared the probe to the prime, reporting whether it was same or different. Reaction times (RTs) to the probe were measured and priming and comparison effects were computed by subtracting RTs of congruent trials (prime and probe are identical) from RTs of incongruent trials (prime and probe differ in shape/color). The engagement of different visual stores was inferred from different priming and comparison effect patterns, which indicated three stages of VSTM processing: an early iconic visible persistence, an intermediate informational persistence, and a later visual working memory. The existence of the first two of these stages is supported by Coltheart's (1980) partitioning of iconic memory into visible persistence and nonvisible informational persistence.

As noted above, in Jacob et al.'s (2013) study, a probe stimulus followed a prime stimulus at varying stimulus onset asynchronies (SOAs), and participants reported the feature of the probe (in a priming task) or compared the probe to the prime (in a comparison task). To further explore the stages of processing reported in this study, post-stimulus processing will be investigated using Sternberg's memory scanning paradigm (1966), in which observers view a memory display and are later shown a single probe item at central fixation to report whether or not it was in the memory display. Performance on this task is directly related to the comparison task of Jacob et al.'s experiment, particularly when the memory display has 1 item to be compared to the probe. By using the memory scanning paradigm, one can increase the number of items (memory load) in the memory display, to assess how memory load affects RT and comparison effects (ΔRTs) across the different stages of VSTM processing. Sternberg (1966) reported that at a probe delay of 2 s, RTs increase as the number of memory display items to be held and scanned in short-term memory increase, indicating limits to the speed of visual processing of multi-item information stored in short-term memory. In addition to the RT measures, the increase in load also allows us to investigate memory capacity by assessing hits and false alarm rates used to compute *k*, a measure of storage capacity, across VSTM stages (Cowan 2001, 2013; Pashler, 1988). An assessment of comparison effects, scanning slope and capacity across SOA would allow a deeper understanding of processing and cognitive resource allocation in each stage of VSTM. Thus, the first objective of the current study is to further explore previous findings on multi-stage VSTM processing when the number of items in VSTM is increased, by investigating, in addition to comparison effects, VSTM scanning slopes (amount of time spent processing an item) and VSTM capacity estimates as memory load increases.

Of additional interest is exploring visual processing when the order of display and target item is reversed. In a visual search task, observers are presented with a probe item, later followed by a search display, where they report whether or not the probe was present in the search display. This task allows understanding of post-stimulus processing when the probe precedes the display (the opposite presentation order of the memory scanning task). Like the memory scanning paradigm, past research also shows that increasing the number of items in search display yields longer RTs (see Wolfe, 1994 for review). A second objective of the current study is to understand how memory scanning slopes compare with visual search slopes, i.e. the comparison of time spent scanning VSTM and of time spent searching a visual display for the probe. Although prior studies (Sternberg, 1966; Wolfe, 1994) indicate that the slopes for visual search ought to be shallower than those for VSTM scanning, no direct comparison between search and scanning slopes, obtained from the same observers, has yet been made.

In addition to the number of items held in memory, processing of information in VSTM is also affected by feature variations (Eng, Chen & Jiang, 2004) and stimulus duration (Potter & Levy, 1969). Preliminary experiments, using the same observers throughout, tested the effects of set size (number of items in the display), stimulus feature and stimulus duration on processing in memory scanning and visual search paradigms at an SOA of 1200 ms, a value at which comparison effects in Jacob et al.'s (2013) previous study attained a maximum in the working memory processing stage. A simultaneous condition was also run, in which there was no temporal separation between probe and display (SOA=0ms). Results indicated that, as expected, VSTM scanning slopes were significantly higher than visual search slopes, and that overall, color features were processed faster than shape features. The value of the slope obtained in the simultaneous condition fell between those obtained in the VSTM scanning and visual search tasks. Memory capacity estimates obtained at an SOA of 0 ms (simultaneous condition) did not differ from those obtained at an SOA of 1200ms when the memory display contained either 1 or 3 items; i.e., when only 1 or 3 items had to be held in VSTM, both well within the VSTM capacity limit. However, when the VSTM display contained 5 items, at or beyond the VSTM capacity limit, memory capacity estimates were lower at 1200 ms than at 0 ms. The higher capacity estimates obtained at an SOA of 0 ms are consistent with the general assumption that iconic processing capacity is higher than processing capacity of visual working memory operative at the SOA of 1200 ms. To relate these findings to the three stages in VSTM, the current study ran the memory scanning and visual search tasks used in the preliminary study over the same range of SOAs sampled by Jacob et al. (2013). The third objective of the current study is to use these memory capacity estimates to better understand processing across the proposed VSTM stages.

The fourth objective is to investigate the generality and validity of Jacob et al.'s (2013) results, specifically the possible role of variations of cognitive strategies on the characteristic fluctuations of comparison effects and priming effects in the three proposed stages. Jacob et al. (2013) sampled SOAs within the first 2 seconds, and conducted priming and comparison tasks by presenting trials blocked by SOA. Preliminary results tested priming and comparison effects by sampling SOA over the first 4 seconds of post-stimulus processing, revealing, in addition to the proposed three VSTM processing stages, a possible fourth additional stage of working memory processing. However, an alternative to the fourth-stage explanation is that participants may have adopted a strategy to maintain information in one or more VSTM stages for a longer period in the long-range SOA condition, thereby resulting in an overall rightward shift (toward higher SOAs) of the three stages relative to those obtained in the short-range condition. Thus, to clarify this interpretive ambiguity, the current study ran separate groups of participants on a short range of SOAs, sampling within the first 2 seconds, the same SOAs tested by Jacob et al. (2013), and on a long range of SOAs sampling the first 4 seconds, including those in the short-range study. Comparing the results of the two studies will confirm whether the effects between 2 and 4 seconds of post-stimulus processing depict the existence of an additional, fourth stage of VSTM, or are a result of strategically extending the durations of the three VSTM stages. In addition, strategic effects may depend on whether the SOA is kept constant in a block of trials (and randomized across blocks) or is randomized within a block of trials. In order to investigate the role of such possible strategic effects, if any, in the stages of VSTM processing, short- and long-range SOA experiments were run with trials blocked by SOAs (SOA-blocked condition), and also with blocks of trials in which all SOAs are tested in a randomly intermixed order (SOA-intermixed condition).

Part 1. Measuring Post-Stimulus Processing Under Variable VSTM and Visual Search Loads

As noted in the Introduction, the preliminary results demonstrated a difference in VSTM capacity, *k*, between the simultaneous condition, when both the VSTM display and probe were presented simultaneously (SOA of 0 ms), and the memory scanning condition, where the probe followed the VSTM display at an SOA of 1200ms. Also, there was a clear difference in VSTM scanning slopes and visual search slopes when number of items (colored squares, black shapes) in the display increased at the SOA of 1200 ms. This SOA corresponds to the third (visual working memory) stage of Jacob et al.'s (2013) findings. In order to use VSTM capacity and scanning slopes as measures of post-stimulus processing in addition to the measure provided by the comparison effects reported by Jacob et al. (2013), it is important to follow up the preliminary findings for the range of SOAs tested in Jacob et al.'s study. Using priming and comparison tasks, Jacob et al. (2013) investigated the temporal dynamics of information transfer from iconic to post-iconic stages of processing and obtained evidence supporting multiple information processing stages in VSTM: visible persistence (SOA: 0-133 ms), informational persistence (SOA: 133-700 ms), and visual working memory (SOA: 700-2000 ms).

The following experiments were conducted to further explore properties of post-stimulus processing by investigating (1) change in comparison effects, (2) variations of *k* in the memory scanning task as the number of items held in memory increases, and (3) change in VSTM scanning slopes across SOA. Moreover (4) VSTM scanning slopes will be compared to visual search slopes within the same set of observers.

Experiments

Visual Search and Scanning of VSTM over a range of SOAs

Using three VSTM loads in the scanning and three similar search display loads in the visual search tasks, comparison effects, VSTM scanning slopes, visual search slopes, and VSTM capacity estimates, *k*, are measured over SOAs ranging from 0 to 1920 ms. Regarding the VSTM measures, the same range of SOAs from the Jacob et al. (2013) study was used in order (a) to explore the effect of load on processing in the proposed stages of VSTM, and (b) to assess if and how scanning slope and estimates of *k*, in addition to comparison effect, can be used to diagnose what happens during the proposed stages of post-stimulus processing (explained in further detail below).

a. Comparison effects as function of VSTM load and SOA

In previous work (Jacob et al., 2013) demonstrating multiple stages of VSTM, observers were required to hold only one item in memory during the comparison task, similar to the one-load condition in the proposed experiment. We know that RTs increase as the number of items increased in memory scanning paradigm (Sternberg, 1966). Accordingly, the preliminary results demonstrated an increase in reaction time as the number of items in the display increases. Requiring observers to process and retain more items in VSTM is expected to yield results shedding light on the role, if any, of load on the SOA-dependent fluctuations of comparison effects, with the fluctuations interpreted as multiple VSTM stages for post-stimulus processing of visual input (Jacob et al., 2013). More resources or slots may be required to process a larger set of items, resulting in either the enhancement of comparison effects (rendering them more prominent) or possibly their decreased amplitude (washing them out). Besides the possible upward or downward shift of the comparison effects, their leftward or rightward shift along the SOA continuum is also possible. Currently, there is no evidence allowing one to hypothesize which of these possibilities should occur as load increases.

b. VSTM capacity estimates as a function of SOA

Measuring *k* at each SOA would provide a better understanding on whether memory capacity is different or constant across the different VSTM stages. As expected, in the preliminary results, *k* was greater at SOA=0 ms (which taps into the visible persistence stage of iconic memory) (k = 2.68) than at 1200 ms (visual working memory stage) (k = 2.453). Given the three distinct stages of VSTM processing (Jacob et al., 2013), *k* estimates should vary as SOA increases from 0 to 1920 ms. This should be particularly evident at the largest VSTM load of 5, which attains or exceeds the capacity limit of visual working memory (Stage 3) but not that of iconic visible persistence (Stage 1).

c. VSTM scanning slopes as a function of SOA

The preliminary results demonstrated that the VSTM scanning slopes varied with the SOA at which the memory display is presented in relation to the single item probe. The preliminary results showed that the scanning slope was high at an SOA of 1200 ms was significantly higher (47.1 ms/item) than at at an SOA of 0 ms (32.0 ms/item). Thus, as the SOA between the memory display and the central single item changes, the VSTM scanning slope should also change. The current experiment investigates the change in scanning slopes as a function of more dense SOA variations between SOAs from 0 to 1920. This allows exploration of the change in scanning slopes across visible-persistence, informational-persistence and working-memory stages of VSTM, which may relate to the stage-specific fluctuations in comparison effects reported in Jacob et al.'s (2013) study.

d. Direct comparison of VSTM scanning slopes and visual search slopes.

The preliminary results also demonstrated that the scanning and search slopes differed at the same SOA of 1200 ms at which the either memory of visual display is presented in relation to the single item probe. Compared to the high value of 47.1 ms/item of the VSTM scanning slope the visual search slope was significantly lower at a value of 15.4 ms/item. By varying the SOA between the (memory of visual) display and the central single probe, one can assess how the slopes of VSTM scanning or visual search compare to each other at each SOA and how each set of slopes varies across SOA. Hence, the current experiment also investigates the change in scanning and search slopes as a function of more dense SOA variations between SOAs from 0 to 1920.

Method

Participants

Ten individuals from University of Houston were recruited for VSTM scanning and visual search tasks. Observers ran in both tasks. The sample consisted mainly of undergraduate and post-baccalaureate students. All had normal or corrected-to-normal vision.

Apparatus

The presentation of stimuli and the recording of responses were controlled using Matlab software vR2012b running on a Dell Optiplex 755 computer with Intel core 2 processor. The monitor was set to a 1280 × 1024 pixel resolution, at a viewing distance of 67.5 cm. The refresh rate of the monitor was 75 Hz.

Procedure

The current experiment followed the same design as the preliminary experiment. Memory scanning

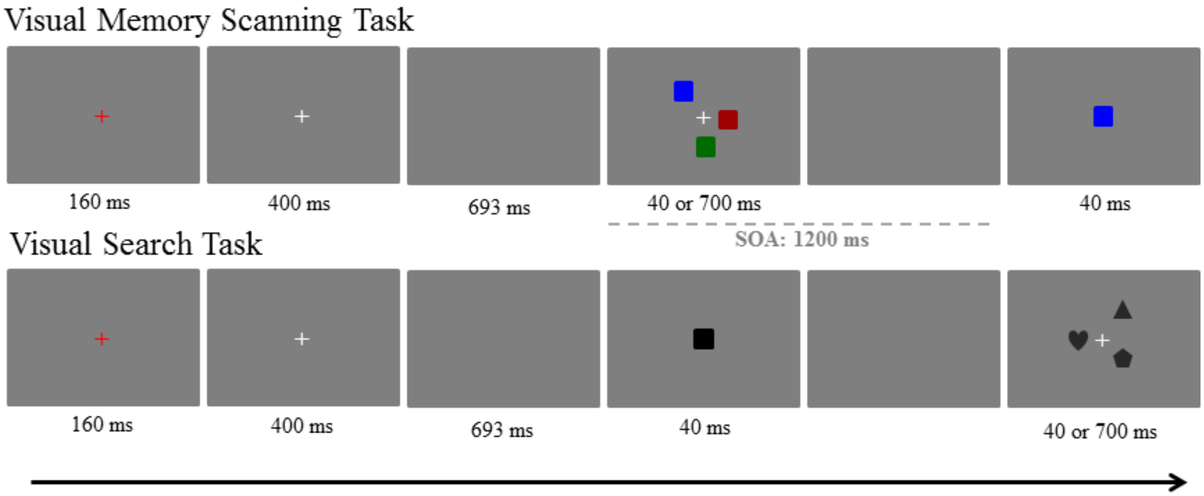


Figure 1. Depiction of the sequence of presentation of probe and 3-item display in visual memory scanning and visual search tasks. A fixation cross appears at the center of the screen for 560 ms, followed by a blank screen for 693 ms. In the scanning task, at varying SOAs after the onset of the memory display, a 40 ms probe appears at fixation; In the search task, after the onset of the 40 ms probe at fixation, a search display appears at varying SOAs. Observers were given up to 3 s after the onset of the probe in the scanning task, and the search display in the search task, to respond. The search and memory displays were presented for 40 ms. Color (shown in memory scanning) and shape (shown in visual search) stimuli were tested in both scanning and search tasks.

and visual search tasks were used to assess the nature of form and, separately, of color feature processing, as the number of items searched or scanned in memory varied. In the memory scanning task, observers were presented a memory display of 1, 3 or 5 items (colored squares, or black shapes) around fixation (see top of Figure 1), followed at an SOA varying from 0 to 1920 ms by a single 40-ms probe item presented at fixation, which observers compared to the memory display, reporting as rapidly and accurately as possible whether or not it matched any item from the previous display. This order was reversed in the visual search task: a search array of 1, 3 or 5 items presented near to, and surrounding, fixation after the onset of the prior single-item probe (see bottom of Figure 1). Observers reported whether the probe was present in the visual search display. Visual search and VSTM scanning tasks were run over a range of 10 SOAs separating the probe from the display: 0, 40, 133, 240, 480, 720, 960, 1200, 1400, and 1920 ms. These SOAs are the same as those used in priming and comparison tasks by Jacob et al. (2013), in order to assess the nature of effect of load on comparison effects and scanning slopes in the three proposed stages of post-stimulus processing in VSTM. The colors (red, blue, green, violet, teal, brown, light grey and black) used in the color trial condition were all equiluminant at 36 cd/m^2. The shapes (circle, square, rhombus, pentagon, triangle, cross, heart and crescent) in the shape trial were all black (6 cd/m^2). All stimuli were 1.5x1.5 degrees at a viewing distance of 67 cm, presented on a uniform dark-grey background (16 cd/m^2). All viewing was binocular. On half of the trials, the central item matched one of the items in the search/memory display (match trial), while on the other half of the trials, the central item did not match any of the display items (mismatch trial).

Participants ran in two sessions, one devoted to each of the two tasks. Order of task was counterbalanced across observers. Within each task session, separate trial blocks were assigned to each of the form- and color-response tasks, in counterbalanced order. Additionally, within each of the feature-response blocks, SOA also was counterbalanced across separate blocks of trials. Each SOA block consisted of 60 trials, with 30 match trials and 30 mismatch trials. The 0-ms SOA condition, in which the central item and the surrounding item array were presented simultaneously for 40 ms and observers reported whether or not any of the items in the surrounding array matched the central item, similar to the comparison task at SOA of 0 ms in Jacob et al.'s (2013) study. Since it clearly relies on processing of both the central item and the surrounding display at the iconic level of processing, it allows exploration of early post-stimulus processing, particularly during the iconic visible persistence stage of VSTM. At all SOAs, the display items to be held in VSTM or to be visually searched were presented in one of 8 positions, excluding the central position, of a notional 3x3 matrix centered at fixation, with the central position reserved for the probe item.

Results

Comparison Effects

A 2 (task: scanning, search) x 2 (feature: form, color) × 3(display size: 1,3,5) x 9 (SOA) repeated-measures ANOVA was performed on comparison effects (ΔRTs). As expected from Jacob et al.'s (2013) results, there was a significant main effect of stimulus feature [*F*(1,18)=4.895, *p*=0.040], as there were larger differences between match and mismatch trials for shape (69.04 ms) than for color (35.75 ms). The main effect of display size also was significant [F(2,18)= 57.643, p=.008], as ΔRTs increased as the number of items to be searched in the display or scanned in memory increased. There also was a significant two-way interaction between

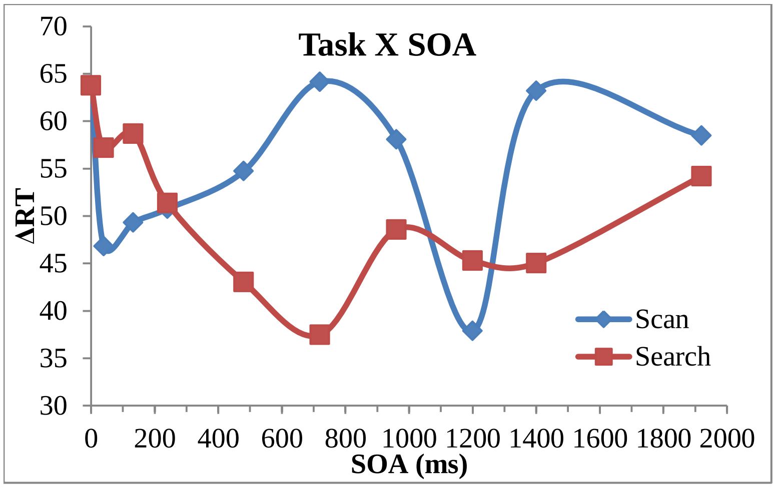


Figure 2. Depiction of average comparison effects for VSTM scanning and visual search tasks across SOAs.

stimulus feature and display size [$F(2,20)= 73.538$, $p<0.001$], as comparison effects increased with display size for shapes but not for colors. Also replicating the results reported by Jacob et al. (2013), another significant two-way interaction was observed between task and SOA, as comparison effects of both tasks behaved differently across early to later SOAs (see Figure 2). In the VSTM scanning task, overall ΔRTs across SOAs followed the multi-phasic nature as seen in Jacob et al.'s results (2013). After the initial drop in ΔRTs over the first 100 ms, as expected in the visible persistence stage, ΔRTs increase steadily to peak at the SOA of 720 ms, and then decrease to a minimum at the 1200 ms SOA. Assuming that this is the second intermediate stage of informational persistence, note that the length of this stage, when ΔRTs are averaged across memory scanning of 1, 3, and 5 items, is longer (130-1200 ms) than what is reported by Jacob et al. (2013) (130-700 ms). This discrepancy between results can be explained by the difference in the number of items that need to be encoded into memory in a single-item load (Jacob et al., 2013) as compared to the current 1-5 item load. As the (average) number of items to be encoded increases, the length of the encoding (informational persistence) stage increases in response to the larger demand on VSTM. Due to this shift to longer post-stimulus intervals, the third visual working memory stage begins at 1200 ms, which is 500 ms later than the start of Jacob et al.'s third stage.

To further understand the intermediate encoding phase and the role of load, a 2 (feature: form, color) × 3(display size: 1,3,5) x 10 (SOA) repeated-measures ANOVA was performed on ΔRTs of the VSTM scanning task and separately for the visual search task. For the VSTM scanning task, the SOA-dependent ΔRT difference across the different display sizes were of particular interest, as they showed a clear rightward shift toward longer SOAs in the second stage as the number of items to be encoded increased. This interpretation is supported by a significant interaction between display size or memory load and SOA [$F(18,162)= 1.709$, $p=0.042$]. Furthermore, overall ΔRTs in this stage tended to increase (see Figure 3a).

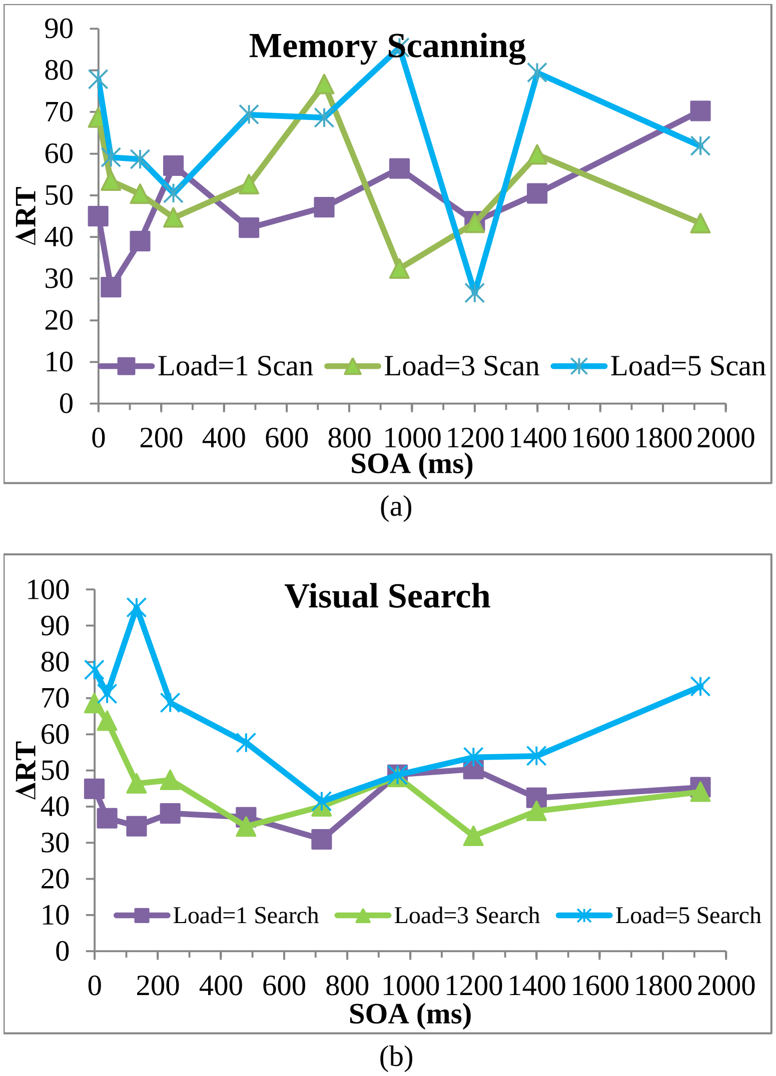
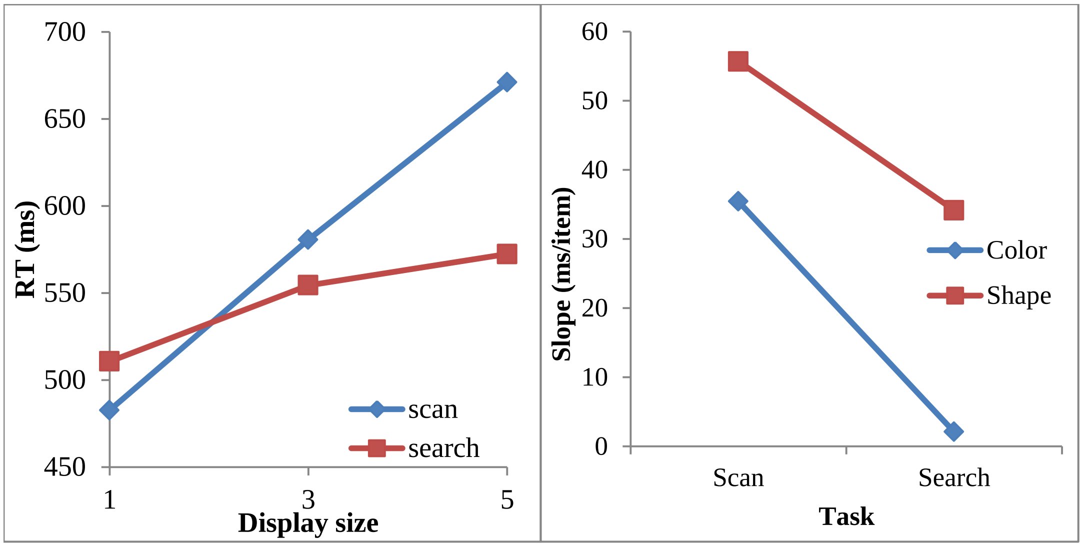


Figure 3. ΔRTs as a function of SOA for (a) the memory scanning task and (b) the visual search task. For details, see text.

In contrast, the visual search task failed to show a similar shift to longer SOAs as the number of items in the search display increased, although the interaction between load and SOA was nearly significant [F(18,162)= 1.656, p=0.053], and it did show a similar increases in ΔRTs, confined to early and late SOAs, as display size increased [F(2,18)= 9.239, p=0.002] (see Figure 3b). Since only the probe item is held in VSTM for all visual search display sizes, the ΔRT results in the visual search task do not reflect shifts of the encoding stages that were found the VSTM scanning task, which depends on VSTM load; instead they appear to show how processing of the single probe item interacts with the processing of the variable-size visual search display.

Scanning and Search Slopes

Scanning and search slopes were computed, separately for each feature, and within feature, separately for each SOA, by first plotting for each observer his/her average overall RT at each of the three display sizes. A linear trendline was fitted for the three data points, and the slope of the trendline was



(a) (b)

Figure 4. (a) Average RTs for VSTM scanning and visual search tasks at each display size, and their slopes from fitted linear trendlines. (b) Feature x task interaction: there is a greater difference in slope between color and shape for the search task, compared to the VSTM scanning task.

acquired. The slope is a good diagnostic tool of the nature of VSTM processing as it accounts for processing of all 3 display sizes in terms of the amount of time spent processing each additional item (ms/item). A 2(task: scan, search) x 2(feature: color, shape) x 9(SOA) repeated-measures ANOVA was performed on the slopes. There was a significant main effect of task[F(1,9)= 451.440, p<0.001], as the VSTM scan slope, as expected, was larger (48.6 ms/item) than the visual search slope (18.1 ms/items); i.e., searching for the probe among visual display items was overall faster than scanning for its presence among the VSTM items (see Figure 4a). There was also a main effect of feature [F(1,9)= 40.085, p<0.001], as color features were processed faster (20.6 ms/item) than shape features (46.0 ms/item). There was a significant task by feature interaction [F(1,9)= 5.365, p=0.046] due to a greater difference between shape and color visual search slopes than the difference between shape and color VSTM scanning slopes (see Figure 4b). There was also a significant interaction between task and SOA [F(8,72)= 6.776, p<0.001], as VSTM scanning slopes generally mirrored visual search slopes across SOAs (see Figure 5), as shown by a negative correlation between scan and search slopes across SOAs [$r(8) = -.887$, $p<.05$]. Interestingly, the highest VSTM scanning slope and the lowest visual search slope occur at the same SOA, 480 ms, which falls into the iconic informational persistence stage, the second stage, intermediate to the first, iconic visible persistence stage and the third, VWM stage of post-stimulus processing.

VSTM Capacity (k)

As proposed, memory capacity estimates (k) for the VSTM scanning task were also computed (using Cowan’s (2013) formula for center probes) and analyzed using a 2(feature: form, color) x 10(SOA) x 3(display size(VSTM load) : 1,3,5) repeated-measures ANOVA. Prior studies (Eng et al., 2005) showed that memory capacity for color is larger than for shape. Thus, as expected, the present findings yielded a main effect of feature [F(1,9)= 6.727, p=0.029], since overall there was a higher memory capacity for color features (k=2.5) than shape features (k=2.2). As also expected, there was a significant main effect of SOA [F(9,81)= 8.544, p<0.001], with early SOAs within iconic memory yielding higher k than later, post-iconic SOAs; and a significant main effect of display size [F(2,18)= 138.637, p<0.001], with k increasing as the number of items in the memory display increases. (However, this increase is trivially a result of the fact that, when the VSTM load is below its capacity of 4-6 items (Cowan, 2010; Luck & Vogel, 1997), the computed capacity estimate, k, must increase as load increases from 1 to 5). Moreover, there was a significant two-way interaction between SOA and display size [F(18,162)= 4.792, p<0.001], as k is nearly constant across SOAs when VSTM load=1, whereas it is largest at the 0-ms SOA and decreases to a lower plateau at SOAs

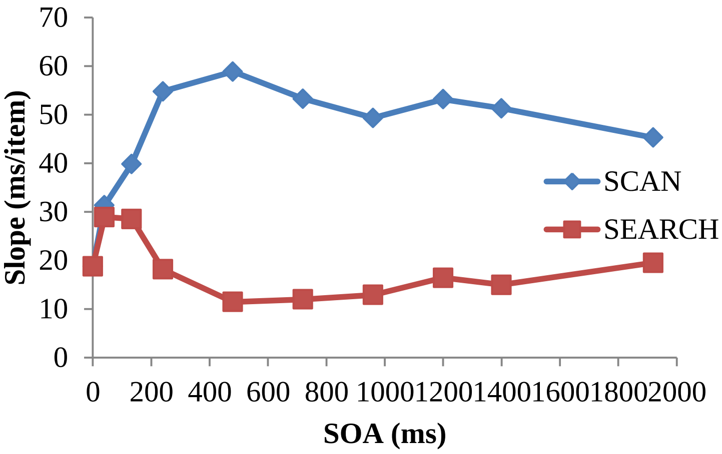


Figure 5. VSTM scan slopes and visual search slopes across SOAs. Note that the two functions generally mirror each other.

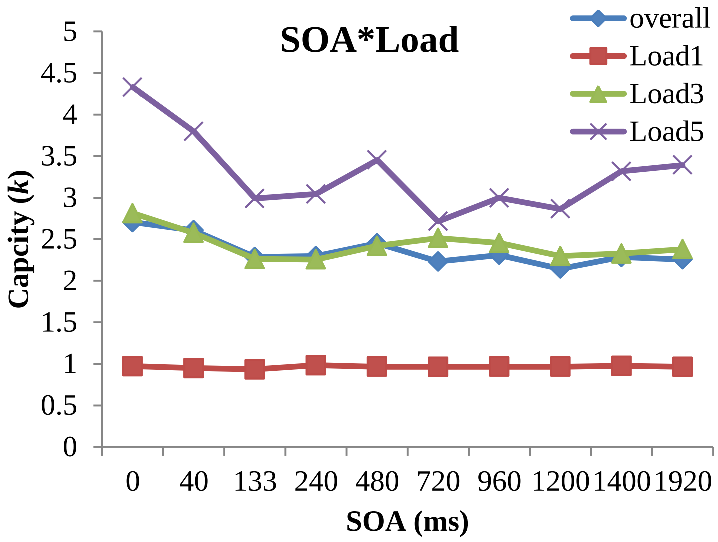


Figure 6. Nature of change in memory capacity estimates across SOA as the number of items in the display (load) increases.

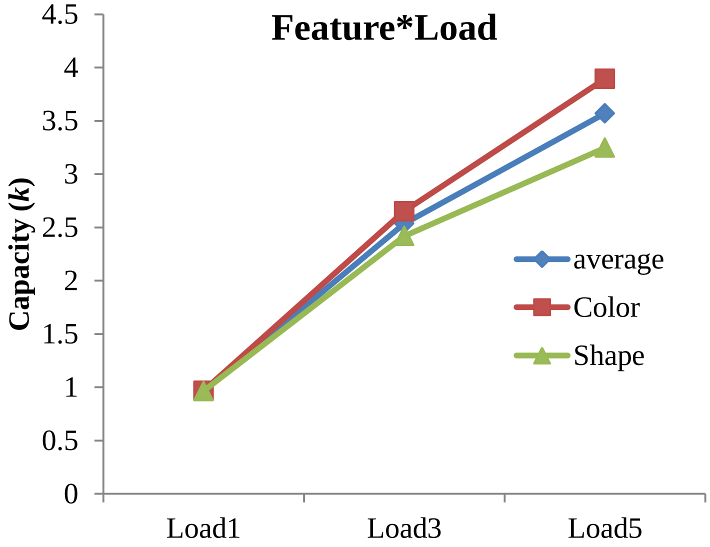


Figure 7. Memory capacity estimates increase with number of items in the display (load). Note that at load 1, there is no difference between color and shape features. However, at load 5, there is a difference between *k* for color and shape features.

beyond 133 ms for VSTM loads of 3 and 5 (see Figure 6). Finally, there also was a feature by VSTM load interaction [F(2,18)= 6.130, p=0.009], due to the increasing difference between *k* for color features and shape features as display size increased (see Figure 7). This difference is particularly prominent at a load=5, where VSTM capacity is attained or exceeded, in line with results reported by Eng et al. (2005).

Discussion

The memory scanning task allowed further exploration of the VSTM processing stages by Jacob et al. (2013), by adding variable memory load demands (low = 1 item to high = 5 items) in VSTM, to explore its effect on these stages. As shown in Figure 2, the average comparison effects across SOAs in the memory scanning task demonstrate these three stages. Within the first 100 ms, ΔRTs decrease, matching Jacob et al.'s (2013) comparison effect trends in the visible persistence stage. This is followed by an increase in ΔRTs peaking at 720 ms SOA and declining until 1200 ms SOA, which is indicative of the second intermediate information persistence stage, where information is being transferred from the first stage into the third, visual working memory stage, in turn followed by the increase in ΔRTs again at 1400 ms. The elongated second stage is further explained by the rightward shift along the SOA axis of the peak values of ΔRTs in this second stage, which is modulated by the memory load demands of the task, as shown in Figure 3a. When only 1 item was held in memory, the average ΔRT peaked at 240 during the second stage, similar to the comparison effect results of Jacob et al. (2013), as their study only required participants to hold 1 item in memory in the comparison task. The ΔRT peak of the second stage shifts rightward to the 720 ms SOA, when 3 items were held in VSTM, as compared with the 1-item load in VSTM. The ΔRTs when 5 items are held in VSTM are shifted further rightward, peaking at the 960 ms SOA. With each rightward shift, ΔRTs are also overall higher as VSTM load increases.

As shown in Figure 5, scanning slopes also show higher processing time per item from 133 ms to 960 ms during the second stage of VSTM processing. Given that the memory scanning task placed greater demands on VSTM processing with each increment in memory load, this VSTM processing phase may also corresponds to the second, encoding phase, which adjusts to task demands. This would explain the overall prolonged encoding stage in the ΔRT results shown in Figure 2. Accordingly, the VSTM scanning slope is highest during this phase, showing, on average, the most time spent per item when scanning VSTM. Given that slopes are derived from RT averages at each load level, the maximum slope attained in the encoding stage is indicative of cognitive processes especially affected by load.

Memory capacity estimates, *k*, of performance in VSTM scanning were also used to better understand the nature of these VSTM processing stages. The value of *k* remained constant across SOAs when only 1 item was maintained in VSTM. This is to be expected because a load of 1 is well below the capacities of iconic as well a visual working memories. When this VSTM load was increased to 3 items, *k*s changed slightly across SOAs; more prominent fluctuations of *k* occurred across SOAs when 5 items were held in VSTM. When VSTM has a higher load (near or beyond working memory capacity limit but well below the iconic memory capacity), there is a decline in *k* during the iconic visible persistence stage up to the 133 ms SOA beginning of the second stage (and beyond), which also correspond to the high processing times (slopes) in the second (and third) stage. Interestingly, at the 5-item VSTM load, memory capacity for color feature processing is much higher than that of form feature processing (see Figure 7). On the other hand, when only 1 item is held in memory, there is no processing difference between color and form; this reflects Jacob et al.'s (2013) finding of no significant difference in VSTM processing of color and form features across SOAs in their comparison task, which required information of only one item (the prime) to be held in memory to compare to the probe.

The visual search task also included different display sizes, however in contrast to the memory scanning task, only one item (the probe) was encoded in memory during the task, in all visual display size conditions. ΔRTs in the visual search task became more pronounced during early and somewhat less pronounced during late SOAs as the display size increases, but there is no overall shift of ΔRT functions to higher SOAs as search display size increased, in contrast to what was seen in memory scanning results. As shown in Figure 5, visual search slopes increase from about 20 ms/item at an SOA of 0 ms to 30 ms/item at SOAs of 40 and 133 ms, both within the visible persistence stage, during which the visible percept of the probe decays as SOA increases from 0 to 133 ms. The higher processing time for the search task during this later phase of the visible persistence stage of probe processing correspond to and may explain the pronounced ΔRT differences at these early SOAs. In contrast to the high VSTM scanning slopes during the second stage, the visual search task slope is lowest during this phase.

Part 2: Investigations of task-dependent strategic effects using priming and comparison tasks

The fourth objective of the study was to further investigate the validity and generality of the findings of Jacob et al.’s (2013) study. In a preliminary experiment, we assessed priming and comparison task performance using a longer range of SOAs between 253 ms to 4000 ms, and found priming effects and comparison effects also to fluctuate over this longer SOA range (Jacob & Breitmeyer, 2013b). The priming effect in the longer SOA range (253-4000 ms) lasts about two times longer than Jacob et al.’s (2013) finding, ending only around 1500 ms as compared to 700 ms in during the shorter SOA range of 0-1900 ms (see upper panel of Figure 8). This suggests that participants may be strategically retaining information about the prime in the visuomotor system for longer durations when SOAs are sampled at correspondingly longer ranges for the priming task. The comparison effects obtained over the longer range of SOAs nearly superimposed on the stages of

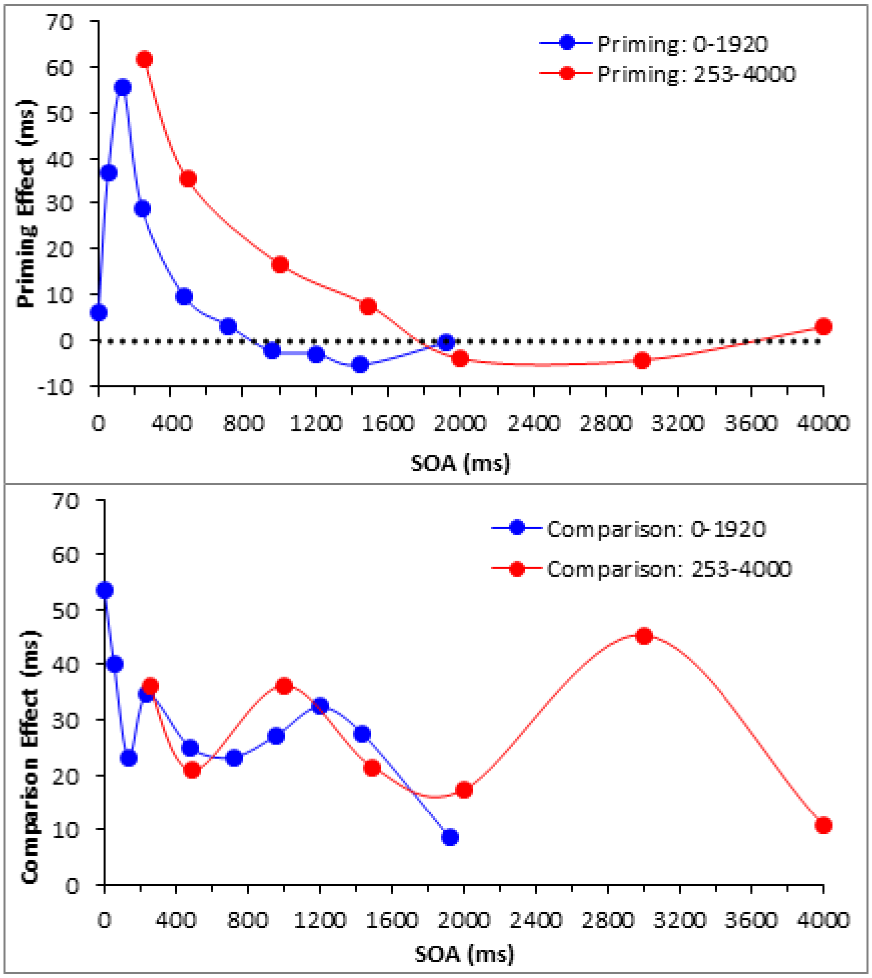


Figure 8. Top: Priming effects are shifted over to larger SOA values in the long-range SOA (red:253-4000 ms) experiment, compared to the short-range SOA (blue: 0-1920 ms) experiment reported by in Jacob et al. (2013). Bottom: Comparison effects in short- (blue) and long-range (red) SOAs demonstrate Jacob et al.’s (2013) three stages of VSTM, with possible existence of fourth stage as indicated by the peak at 3000 ms.

VSTM indicated by the comparison effects obtained by Jacob et al. (2013) over the shorter range of SOAs (see lower panel of Figure 8). One way to interpret these similarities and differences is that the initial three stages of post-stimulus processing are identical for the short and long ranges of SOAs with the possible existence of an additional fourth stage of visual memory (2000-4000ms) for the long range SOAs. However, another explanation is that the longer range of SOAs required longer maintenance of the prime in not only visuomotor memory but also in the one or more stages VSTM. This would still produce only three stages of VSTM processing in the comparison task, but with an overall shift of the three stages to higher SOAs by elongating their durations across the longer SOA range. To explore these possibilities, we administered priming and comparison tasks, sampling SOAs tapping into the first two seconds and the first four seconds of post-stimulus processing.

Method

Participants

All participants were recruited from the Psychology department at the University of Houston. Twenty eight students participated in priming and comparison tasks over shorter range of SOAs (0-2 s), and separately, 17 students participated in the same tasks sampling the longer range of SOAs (0-4 s). Separate groups of participants were used to prevent possible carry-over effects that might affect performance in a repeated-measures design. These separate groups were tested at the short and at long ranges of SOAs in order to clarify 1) if there is an additional fourth stage of VSTM that is engaged by the long-range SOAs, or 2) if information about the prime is being retained for prolonged durations of only three stages when SOAs are sampled at longer ranges.

Apparatus and stimuli

The same methods previously detailed in Jacob et al. (2013) were used in this study. Priming and comparison tasks were performed in a semi-lit room. The stimuli were displayed at a rate of 100 Hz on a 1,024 × 768 color monitor. Stimulus presentation and response recording were controlled by a

Dell computer. The viewing distance was roughly 80 cm. The prime and probe stimuli were desaturated green or blue (20.0 cd/m2) diamonds or squares (0.86° × 0.86°), presented on a gray (12.3 cd/m2) background. In each trial, the color of the stimuli varied while their shape was kept constant. Within each block, the trials were further divided so that on half of the trials, the prime and probe stimuli matched (e.g., blue prime and blue probe), and on the other half of the trials, the prime and probe stimuli mismatched (e.g., green prime and blue probe) (see Figure 9). The prime was centered 1° below fixation, and the probe was centered 1° above fixation.

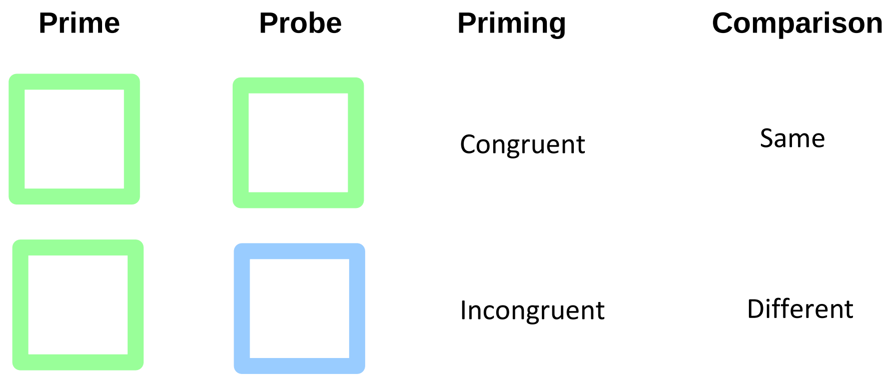


Figure 9. Depiction of matching and mismatching prime-probe pairs in priming and comparison tasks.

Procedure

For one group, the prime stimulus preceded the probe stimulus at a short range of SOAs: 0, 40, 130, 240, 480, 720, 960, 1200, 1400, and 1920 ms. The other group was tested at a longer range of SOAs: 0, 40, 130, 240, 480, 720, 960, 1200, 1400, 1920, 2200, 2480, 2760, 3040, 3320, 3600, 3880, and 4160 ms. The longer range contained all of the SOAs in the shorter range. The durations of the prime and probe were 40 ms each. While stimulus presentations in both tasks were identical, the instructions varied. In the priming task, observers were instructed to report, as quickly and accurately as possible, the color of the probe. Similarly, in the comparison task, observers were instructed to report whether the color of the probe and prime matched or mismatched. Additionally, in order to investigate the role of strategic effects, if any, in the stages of VSTM processing, each task was run twice: (1) with trials blocked by SOAs (SOA-blocked condition), and (2) in blocks of trials in which all SOAs are tested in a randomly intermixed order (SOA-intermixed condition). In the blocked condition, each SOA block consisted of 80 trials, with 40 trials devoted to each of the matched and mismatched prime–probe pairings. In the intermixed condition, each block consisted of 80 trials, with each SOA being occurring 8 times (4 match trials, 4 mismatch trials). The order of blocked and intermixed conditions was counterbalanced across observers, and within these conditions, the order of priming and comparison task also was similarly counterbalanced. Additionally, in the SOA-blocked condition, the order of SOA within a task was counterbalanced across observers.

Results

Short-Range SOAs

A 2 (task: priming, comparison) x 2 (blocked, intermixed trials) × 10 (SOA) repeated-measures ANOVA was performed on ΔRTs in the short-range SOA experiment. As expected from previous findings (Jacob et al., 2013), a significant main effect of task [F(1,27)=6.234, p=0.019] reflects overall smaller ΔRTs in the priming (8.4 ms) than in the comparison (18.9 ms) task. A significant interaction between task and SOA was also observed [F(8,144)=4.637, p<0.001], due to the rapid decline in priming effect as SOAs increase, while comparison effects remained significantly above zero (t(9)=10.757, p<0.001). As illustrated in Figure 10, priming and comparison effects show characteristic fluctuations indicative of the three stages of VSTM processing proposed by Jacob et al. (2013): priming effects increase rapidly between the 0 and 40 ms, and generally decline across the rest of the SOAs, while comparison effects remain above zero across all SOAs. Priming effects and comparison effects were separately submitted to a 2 (blocked, intermixed trials) × 10 (SOA) repeated-measures ANOVA. Whereas a significant main effect of the type of trial (blocked, intermixed) and its interaction with SOA was obtained in the priming task, neither effect was significant in the comparison task. Particularly at the earlier SOAs priming effects were larger for trials blocked by SOA than when SOAs were intermixed in each set of trails (see Figure 10).

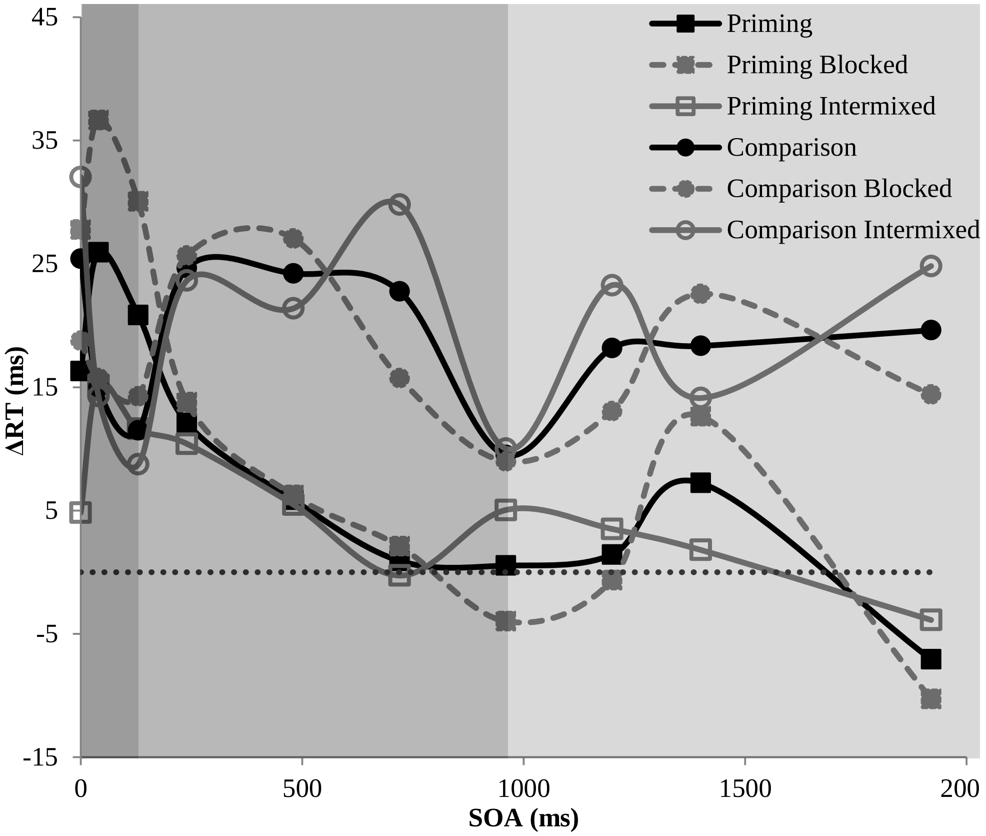


Figure 10. Priming effect increases between the 0 ms and 40 ms SOAs, and declines to 0 through the 1200 ms SOA. The comparison effect fluctuates, remaining above 0 throughout the SOAs. Both effects (see black lines) show characteristics fluctuations of the 3 stages of VSTM processing, as shown in Jacob et al. (2013). Priming and comparison effects when trials were blocked by SOA (see dotted grey line) and when SOAs were intermixed in each block (see solid grey line). Note the difference between both effects during the early SOAs, demonstrating a role of strategic effects in the priming effect during SOA-blocked trials.

Long-Range SOAs

A 2 (task: priming, comparison) x 2 (blocked, intermixed trials) × 18 (SOA) repeated-measures ANOVA was performed on ΔRTs in the long-range SOA experiment. Similar to the results of the short SOA range, there was a significant interaction between task and SOA [F(17,289)=1.775, p=0.031], as priming and comparison effects differed in trend across SOA. T-tests confirmed that the priming effect is significantly different from baseline for the first 3 SOAs (0, 40, and 130 ms) and the 1400 ms SOA. Thus, the priming effect diminishes to near zero at SOAs beyond 130 ms, with the

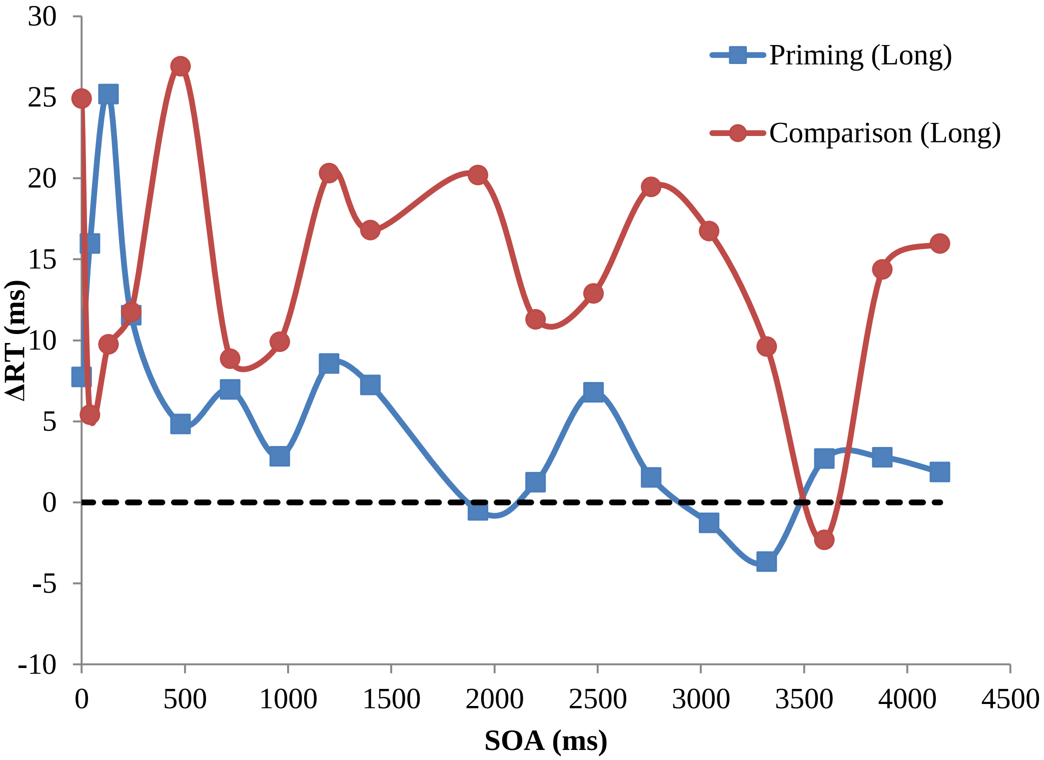
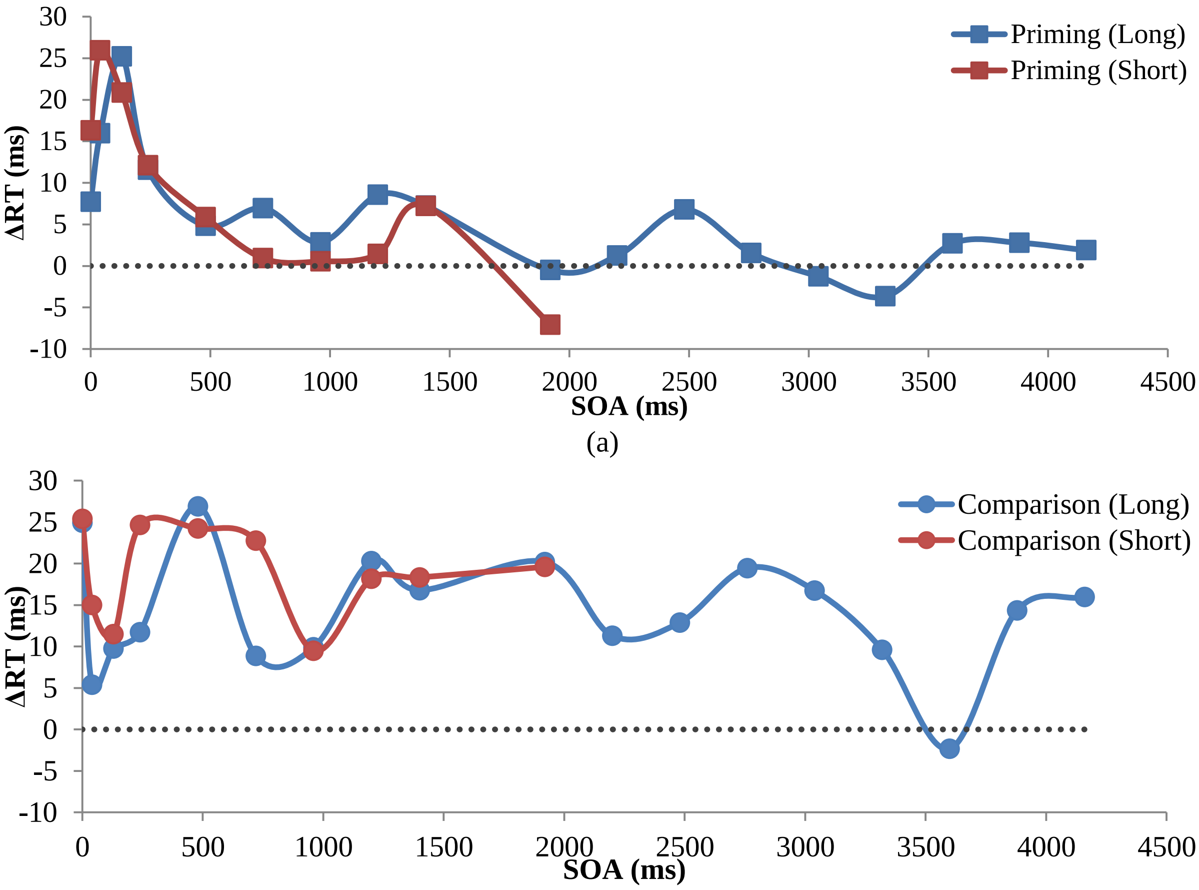


Figure 11. Priming and comparison effects over the long-range of SOAs. Within the first 2 seconds of post-stimulus processing, both effects follow the trends in accordance with the three proposed stages of VSTM in the first 2000 ms of post-stimulus processing, and are different in nature from each other.

exception of the 1400-ms SOA. In contrast, the comparison effect shows SOA-dependent variations, being significantly different from baseline at SOAs 0, 40, 130, 480, 1200, 1920, 2760, and 3040 (see Figure 11).

Comparison of ΔRT in short- and long-range SOA conditions in overlapping SOA ranges (0-1920 ms)

Additionally, priming and comparison effects from both SOA-range experiments for the SOAs within 0-1920 ms were submitted to a 2(SOA range: short, long) x 2 (task: priming, comparison) x 2 (blocked, intermixed trials) × 10 (SOA) repeated-measures mixed ANOVA, which, for both tasks, showed no significant difference between ΔRTs between the two SOA ranges [F(9,153)=0.833, p=0.587]. Unlike the preliminary results, the priming effects obtained over the longer range of SOAs nearly superimposed on the stages of VSTM indicated by priming effects obtained over the shorter



(a)

(b)

Figure 12. Depiction of priming effects (a) and comparison effects (b) of short-range SOA experiment superimposed onto the effects from the long-range SOA experiment. Note that the comparison effects from the long-range SOA experiment not only demonstrate fluctuations characteristic of the proposed three stages of VSTM processing from 0-2000 ms SOAs, but are also indicative of additional stage(s) from 2500 to 4000ms SOAs.

range of SOAs [F(9,144)=0.609, p=0.788] (see Figure 12a). Similarly, the comparison effects obtained over the first 1920 ms range of SOAs in the longer-range condition demonstrate the same stages of VSTM as those of the shorter-range condition [F(9,144)=1.082, p=0.379] (see Figure 12b), and suggested the possible existence of additional stage(s) of visual memory (2500-4000ms).

Discussion

Priming and comparison effects in the short-range experiment demonstrated the three stages of post-stimulus processing in VSTM proposed by Jacob et al. (2013), and comparison effects in the long-range experiment showed evidence for an additional fourth stage of VSTM processing. Priming effects in both of these studies peaked within the first 100 ms, tapping into the visible persistence stage, and declined thereafter, characteristic of the second, invisible informational persistence stage. In contrast, priming results in the preliminary experiment showed a shift in priming effect to higher SOAs in the longer-range experiment. This may be an SOA-range specific finding, as the long range of SOAs in the preliminary study sampled between 253ms and 4000ms, whereas the long range of SOAs in the current study included the earlier SOAs of 0, 40, 130 and 240 ms.

Similar to the results in Jacob et al. (2013), comparison effects decline during the first 100ms (visible persistence stage), and then increase at 240ms plateauing through 720 ms and declining at 960 ms (informational persistence), followed by another increase at 1200 ms (visual working memory). The results of the long-range experiment show a similar pattern of performance in both tasks to that of the short range experiment demonstrating the three VSTM processing stages, with the addition of a fourth stage of processing evident especially in the comparison effects between SOAs of 2200 ms and 3600 ms, followed by another increase in ΔRT, which suggests the beginnings of an additional fifth stage. This supports the first explanation for the results of the preliminary experiment. Furthermore, the manner in which trials were presented (blocked by SOA, vs. non-blocked/intermixed) affected only the priming effect across early SOAs in the short-range experiment, as higher priming effects occurred when trials were blocked by SOA. The priming effect across SOAs in the long-range experiment and the comparison effect in both SOA ranges were not influenced by the type of trials. This is indicative that the initial three stages as well as the later stages of VSTM are not an artifact of the manner in which observers are tested.

General Discussion

The current study aimed to answer two questions: (1) What is the effect of memory load on the fluctuations characterizing the three stages of VSTM proposed by Jacob et al. (2013)? (2) Are these fluctuations affected by differential task-specific strategies? In order to answer the first question, memory scanning and visual search tasks were used in Part 1 of the study, using VSTM loads or visual displays consisting of 1, 3 or 5 items. Results revealed higher, more pronounced ΔRTs (differences between RTs to match vs. mismatch trials) at each load increment in visual search and VSTM scanning tasks. ΔRTs in the VSTM scanning task showed similar fluctuations as those reported by Jacob et al. (2013), and showed evidence for the 3 stages of VSTM processing: visible persistence, invisible informational persistence, and visual working memory. Overall scanning results indicated that the second stage was significantly longer (40 – 1200 ms) than the length of the second stage (133-700 ms) reported by Jacob et al. (2013) Separating the results by each load further explained the long second stage: after the initial drop during the visible persistence stage, the ΔRT fluctuation (characterizing the informational persistence stage) shifted rightward to higher SOAs with each increment of VSTM load. In contrast, visual search task results did not show a similar shift as search display size increased. The two tasks differ in nature: in the VSTM scanning task, participants are required to encode and maintain the items in the VSTM display to compare them to a subsequent single probe, whereas in the visual search task, participants only encode and maintain the single probe item in memory and compare it to subsequent items in the search display. The fact that the VSTM scanning results were affected the most during the second stage of VSTM processing indicates that the encoding occurring during this stage is prolonged, reflecting the need for more time to encode the amount of VSTM informational load increases.

What implications does this finding have for other paradigms? Jacob et al. (2013) related their second VSTM stage to the attentional blink (AB), as the timing of their second VSTM stage lines up with the timing and duration of the attentional blink. Traditional AB paradigms present a stream of stimuli at fixation, with two targets, to be identified by the participant. Given the results of the current study, it would be interesting to know how the AB would change when memory load is varied. For example, if instead of a single visual stream, several (2 or 3) visual streams were presented and the targets were to appear in any of the streams, participants would need to spread their processing resources to encompass the encoding of all streams, including the representation of the targets, concurrently. If the ΔRT peaks in the second stage of VSTM processing correlates with the AB and reflects an encoding stage, rather than an iconic memory stage , there should be differences in the duration (and possibly magnitude) of the AB effect, shifting to higher values with higher loads. That is, as VSTM encoding demands increase, the temporal duration of the AB also should also increase.

VSTM scanning slopes showed highest processing time per item in the second stage, further suggesting that encoding may be occurring, as it takes longer to process more items. Scanning slopes within the first 100 ms are realtively low, which is explained by the hypothesis that during the first 100 ms iconic visible persistence is at work (Di Lollo, 1977). Since the VSTM display is still visible during this interval, one would expect the slopes to be relatively close to that obtained at the SOA of 0 ms (simultaneous presentation of VSTM display and probe, when both are maximally visible at iconic levels of processing). After attaining a maximum in the second, encoding stage (100-960 ms), scanning slopes slowly decrease and level off at longer SOAs reflecting the maintenance stage of visual working memory (VWM). The differences between scanning slopes may thus indicate functional differences between each of the three stages. Information enters an initial brief sensory processing in the iconic visible persistence stage, and is encoded into VWM during the second stage, and maintained in VWM during the third stage. If this explanation is correct, what would happen to the three stages of VSTM processing when there is concurrent maintenance in VWM? In the current VSTM scanning study, the encoding phase in particular was affected by directly varying the VSTM . However, what is the effect on the encoding phase when information is concurrently being maintained in working memory during a VSTM scanning task? Since past research shows that concurrent VWM load affects the post-iconic readout and encoding of information into VWM (Treviño, Jacob & Breitmeyer, 2013), the encoding stage in a VSTM scanning task may function as efficiently with concurrent maintenance of items. This could be tested in a dual task paradigm, where a memory VSTM processing is tested using a one-item comparison task, while concurrently 1, 3 or 5 shapes would be held in VWM by the participants. Here a VWM display of 1, 3 or 5 shapes would first be presented. Soon afterward, a simple color comparison task would be performed, where a single prime stimulus is followed by a probe stimulus, to which participants make a speeded match-mismatch judgment regarding the colors of the prime and probe. Immediately after this task they would be probed at fixation with a shape probe that either matches an item or mismatches all items in the memory display. If Stage 2 of VSTM processing involves encoding into VWM, the efficiency of encoding should be reduced as concurrent VWM load increases, perhaps resulting in increasing slopes during Stage 2 as concurrent VWM load increases. On the other hand, ΔRTs for the comparison task may also show increases with memory load, as the memory representation of the prime is weaker when information is being maintained in VSTM. Furthermore, unlike the results obtained in the present memory scanning task, it is possible that the length of the encoding phase may not be affected by concurrent VWM load (no rightward shift to higher SOAs as load increases), as only one item (the prime) would need to be encoded, since the items held in VWM are already encoded. Stage 1 should remain unaffected by concurrent VWM load, as iconic memory has a separate, high capacity for items.

Part 2 of the study examined the role of strategic effects on Jacob et al.'s (2013) proposed three stages of VSTM. Using the same tasks from the original study, short- and long-range SOAs were sampled, and trials were presented in SOA-blocked (all trials in a block have the same SOA) and SOA-intermixed (blocks of trials in which all SOAs are tested in randomly intermixed order) conditions. Comparison of ΔRTs in blocked and intermixed conditions within each task showed that priming effects in the short-range study were significantly higher in the blocked condition than the intermixed condition, suggesting the adoption of trial-specific strategies in the short-range priming task. No significant strategic effects were found for priming effects in the long-range study, and comparison effects in short- and long-range studies.

There also was no significant difference between priming effects obtained in the short- and long-range SOA conditions. However, based on preliminary results in the priming task a rightward shift in effects to higher SOAs was predicted in the longer range. This discrepancy between preliminary and current findings in the priming task may be due to the difference in the range of SOAs sampled in the long-range conditions of both studies. The preliminary long-range SOAs begin sampling at 253 ms, whereas the current long-range SOAs begin sampling much earlier at 0 ms. Thus, the rightward shift to higher SOAs seen in the preliminary priming results may be specific to the later range of SOAs tested. To investigate this, separate groups of observers should be run in an early-SOA-range study, sampling SOAs from, say, 0-800 ms, and a late-SOA-range study, sampling SOAs from, say, 400-1200 ms. Comparison of priming effects at the overlapping SOAs will clarify whether priming effect is affected by the temporal parameters of the task.

ΔRTs obtained in short- and long-range SOAs in the comparison task revealed an additional fourth stage of VSTM processing, between 2480 ms and 3480 ms SOAs and possibly the beginnings of a fifth stage at still higher SOAs. The results of the memory scanning task in Part 1 demonstrated the effect of load on the 3 stages of VSTM, specifically elongating the second stage to account for VSTM load demands. What is the effect of load at SOAs beyond 2 seconds? To investigate, the SOA range of the memory scanning task from part 1, with the several loads were used, could be extended to include the SOAs in the present long-range condition. In Stage 2, increase in load resulted in increased ΔRTs, and a rightward shift along the SOA axis, suggesting that this stage may be the temporal window for the encoding process. Since information is already encoded at longer SOAs, perhaps later stages would have higher ΔRTs without the rightward shift. Also, what is the mechanism causing fluctuations at the longer SOAs? One possible explanation is that maintaining a representation of the primes requires sustained attention which might lapse and thus require rehearsal in VWM via *attentional refreshing*, a term referring the use of attention to maintain the memory trace of an item in an active state. Cowan (1999) explains that the representation of an item is activated when it is in the focus of attention; when the focus is switched or lapses, the representation decays. Before it is completely lost, the focus of attention can be redirected toward the representation to reactivate it. Thus, since the comparison task requires participants to recall the prime in order to compare it to the probe, the representation of the prime must be refreshed over longer SOAs in order to accurately and speedily make match-mismatch judgments. Therefore, if even longer SOAs were sampled, more fluctuations may appear in visual working memory, due to attention lapsing and being redirected to the representation of the prime. Furthermore, if attentional refreshing is necessary to accurately compare prime and probe, comparison of ΔRTs on accurate and inaccurate trials may reveal different trends across SOAs.

If there are in fact 4 (or more) stages of VSTM processing, there are many implications for working memory studies. For instance, the current study required speeded responses. Since working memory studies tend to use non-speeded trials, would these results translate to non-speeded trials? Perhaps the fluctuations would disappear as participants would respond only when they are fairly confident in their response. Since here observers are not under time pressure, representations of the prime and probe may be attended to, refreshed, and strengthened before making a response. Since change detection paradigms are used to study VWM, are there also implications for change detection? If an attentional refreshing mechanism is present, change detection studies using speeded responses may yield different results than when non-speeded responses are used.

The overarching implication with these studies is the importance of timing in the design of VSTM experiments. Often the reason for discrepant findings among different research groups is the arbitrary use of SOAs or ISIs (inter-stimulus intervals) that do not match, resulting in findings that do not match. Change detection experiments have used a variable ISIs: 256 ms, 281 ms (Becker et al., 2000), 500ms (Woodman, Vogel & Luck, 2001); 900 ms (Luck & Vogel, 1977; Treisman & Zhang, 2006), 2000 ms (Sternberg, 1966), etc. Given the different processing stages of VSTM, are each of these research groups hitting different stages or phases of VSTM? An understanding of processing differences across time in post-stimulus processing may help in unifying findings, and further explorations of VSTM processing.

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