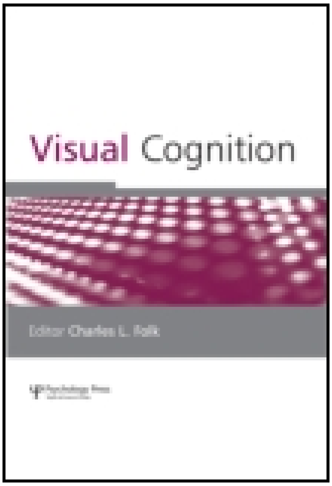

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Independent costs for storing and manipulating information in visual working memory

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By allowing for the storage and manipulation of information in the absence of perceptual input, Visual Working Memory (VWM) supports abilities that are critical to daily functioning. These include the abilities to reason about objects that are no longer visible (Flombaum & Scholl, 2006), to integrate separate visual scenes (Irwin, 1991), and to update representations in the face of new information (Baddeley & Hitch, 1974). A significant portion of previous research has focused on storage costs within VWM, e.g., the maximum number of items or information that can be maintained and their precision. In contrast, less focus has been placed on determining whether there are costs associated with manipulating items in VWM. In a series of four experiments, we provide evidence of manipulation costs in VWM and investigate the source of these costs.

We developed a paradigm in which participants remembered colour information for multiple items, and dynamically updated this information over the retention interval. On each trial (Figure 1a), participants were presented with two to four coloured circles; colours disappeared after the encoding period leaving behind white outlines; pairs of outlines then moved smoothly to swap positions serially for zero to four times; after the swaps were completed, one circle filled in with a colour from the original display and participants had to respond whether that colour was correct for that circle, given the history of the

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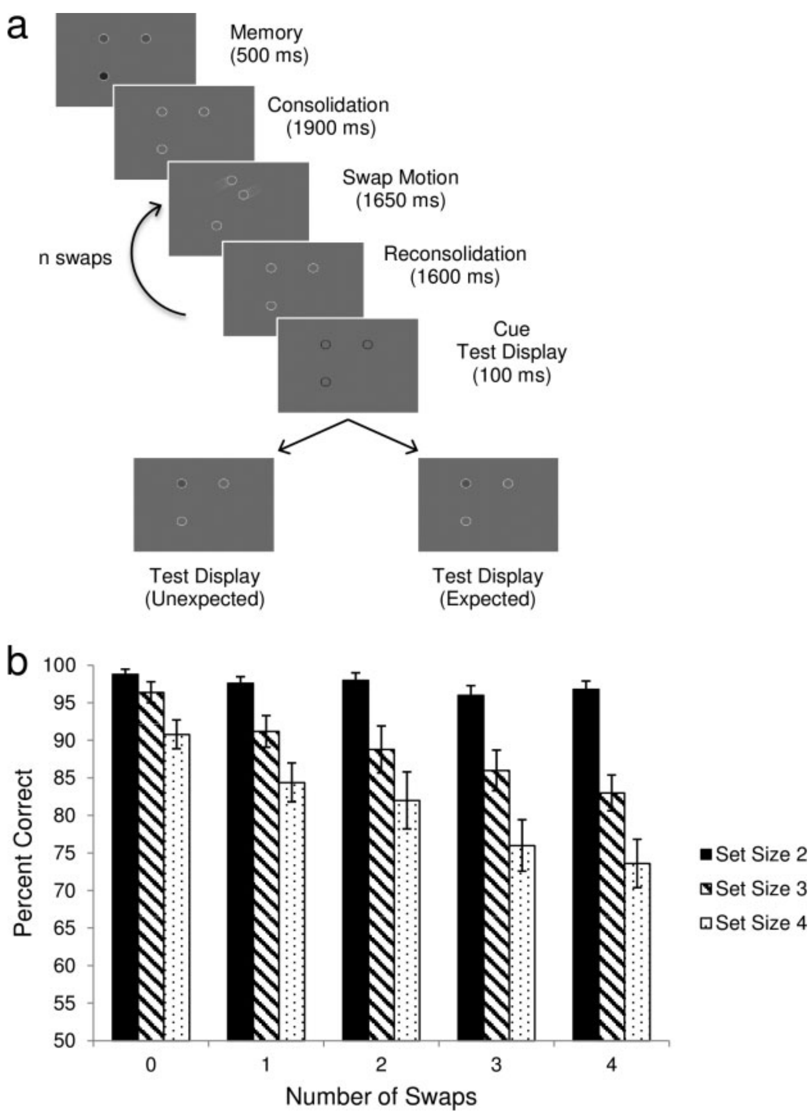

Figure 1. (a) Illustration of a typical dynamic change detection task trial. Patterns represent distinct colours. (b) Results of Experiment 1: Differential effects for manipulating items in VWM. Little to no cost associated with manipulating two items; systematic decrease in performance for manipulating three or four items.

swaps. This task requires binding the initial colours to the outlines, remembering these colours, and updating the spatial positions of colours consistent with the swaps.

In Experiment 1, we determined whether updating spatial locations affects memory for colours. Participants saw 200 trials of 2–4 circles with 0–4 swaps per trial. Performance on zero-swap trials revealed the typical 3–4 item limit of VWM storage (Luck & Vogel, 1997). Performance on 1–4 swap trials revealed little to no cost associated with manipulating two items in VWM, and systematic decreases in performance across swaps when manipulating three or four items (Figure 1b). This interaction between set size and manipulation costs suggests that there are independent limits governing the storage and the manipulation of information in VWM. Control experiments demonstrate that the results cannot be attributed to the use of strategies, such as verbally encoding of the display or selectively tracking a subset of items, or the degradation of representations resulting from a temporal delay.

Experiments 2–4 were designed to investigate the source of spatiotemporal manipulation costs in VWM, and, in particular, the possibility that manipulating information in VWM requires bringing the to-be-manipulated items into a privileged state of selection.

Prior to performing a manipulation, items held in VWM may first have to be selected and brought into a privileged state. As has been previously demonstrated for nonvisual working memory, a “switch cost” (Garavan, 1998; Oberauer, 2002, 2003) might occur in VWM whenever a manipulation requires a shift of focus away from currently active items to a new set of items stored in memory, in contrast to when the same, for example, two items, are manipulated repeatedly and maintained in an active state throughout. Under this hypothesis, the systematic decrease in performance for set sizes 3 and 4 in Experiment 1 may have resulted from a switch cost effect, as the set of items chosen for a manipulation varied throughout the trial. To test this hypothesis, in Experiment 2, we presented participants with a version of our dynamic change detection task where every trial included four coloured circles which were visually separated into two groups of two (using vertical or horizontal grouping bars—shared region). Circle swaps occurred either within one pair multiple times (one-pair trial), or the active pair would vary throughout the trial (two-pair mixed trial). Participants controlled the initiation of switches via buttonpress. The amount of time spent before initiating each swap was recorded and used to test for a “pair-switch cost”, similar to what has been documented for nonvisual working memory (i.e., longer RTs to initiate a swap, or update, following a pair switch compared to repeated-pair events; Garavan, 1998). Consistent with this prediction, RTs were longer following pair-switch events compared to repeated-pair events, suggesting that a shift in focus from one active pair to another may be the source of the switch costs we observed in Experiment 1.

In Experiment 3, we sought to replicate this switch cost effect in the absence of clearly demarcated sets. Participants were presented with four coloured circles without enclosing rectangles and swap types progressed as in Experiment 2. Once more, participants took longer to initiate swaps in the pair-switch trials compared to the repeated-pair trials.

In Experiment 4, we returned to the methods of Experiment 1 and compared four-item mixed-pair trials (i.e., where the active pair changes throughout the trial) to four-item repeated-pair trials (i.e., where a single pair stays in active focus throughout the trial). We found decreasing accuracy as a function of swaps in both conditions along with some savings on repeated-pair trials. This suggests that the "pair-switch cost" associated with changing which pair is actively in focus can account for some, but not all, of the costs associated with swaps on four-item trials. The additional source of manipulation cost remains to be determined.

Taken together, these findings suggest that there are independent limits governing the storage and the manipulation of information in VWM. Further investigations into the manipulation of information in VWM may prove informative towards describing the architecture of VWM and the format of its representations.

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