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Does working memory load facilitate target detection?☆

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Previous studies demonstrated that increasing working memory (WM) load delays performance of a concurrent task, by distracting attention and thus interfering with encoding and maintenance processes. The present study used a version of the change detection task with a target detection requirement during the retention interval. In contrast to the above prediction, target detection was faster following a larger set-size, specifically when presented shortly after the memory array (up to 400 ms). The effect of set-size on target detection was also evident when no memory retention was required. The set-size effect was also found using different modalities. Moreover, it was only observed when the memory array was presented simultaneously, but not sequentially. These results were explained by increased phasic alertness exerted by the larger visual display. The present study offers new evidence of ongoing attentional processes in the commonly-used change detection paradigm.

1. Introduction

Working memory (WM) representations serve to bias attention and action selectively. Maintenance of goal-relevant information in WM is therefore needed to enable goal-directed, top-down processing. However, while engaged in maintaining goal-relevant information in WM, people should also be sensitive to changes in their environment. These changes might be task-irrelevant and thus ignored, but could also be relevant, and in this case may lead to updating WM with new information. The goal of the present study is to examine the relationship between WM load and the ability to detect new information.

Is detection of new information in the environment affected by WM, and if so — in what way? One possibility is that our ability to detect objects would be impaired when increasing WM load, since attention is allocated to WM. This prediction is based on the idea that two opposing demands compete for a limited attentional resource: the demand to maintain information and the demand to search for new information. For example, according to the perceptual load framework (Lavie, 2005), increasing WM demands impairs selective attention. Load on executive control functions, such as WM, taxes performance by interfering with stimulus processing and increases interference by distractors. A common finding in the literature, on which this prediction is based on, is that maintaining information in WM delays processing of new information. Several studies demonstrated slow response times (RTs) in a concurrent task under large memory loads (Shulman & Greenberg, 1971; Shulman, Greenberg, & Martin, 1971; Stanners, Meunier, & Headley, 1969). For example, Saito and Miyake (2004) showed that the reading time for the last sentence in a list of sentences was longer than that of the first sentence in the list. This finding demonstrated that sentence processing is delayed when maintenance load increases. Maehara and Saito (2007) further demonstrated that the increase in processing times with load is not limited to the verbal domain. They used two span tests that required verbal processing with two types of to-be-remembered items: words or dots in matrices. In both the verbal and spatial tests, the later a processing unit (i.e. sentence verification task) appeared in a trial, the slower the sentence's processing speed was. Furthermore, Vergauwe, Camos, and Barrouillet (2014) suggested that processing new information is impaired when information is maintained in WM. They argued that WM operates in a sequential fashion and thus maintenance activities (such as refreshing) postpone concurrent processing. That is, delayed processing increases with the amount of items to be maintained.

A second hypothesis is that detection would be impaired by WM load not because of competition over a limited attentional resource, but due to the role of WM in allocating attention to relevant information. The ability to control attentional processes has been related to WM capacity, namely the size limit of the WM system. For example, Engle (2002) suggested that higher WM capacity is a result of improved selective attention abilities and not a result of a larger memory store. Considering that goal-directed processes depend on the ability to control, in a top-down manner, the stimuli that will be processed (due to limited processing capabilities), attention can be conceptualized as a “gatekeeper” in the service of WM (Awh, Vogel, & Oh, 2006). That is, attention can bias detection and encoding of items that are more relevant to the current goal.

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This view was supported in a recent study by Sörqvist, Stenfelt, and Rönnberg (2012). Sörqvist and colleagues used the n-back task with $n = 1$, 2 or 3 items, and measured the evoked potential brainstem response to an irrelevant sound. The results showed decreasing brainstem response as a function of WM load. Also, individual differences in WMC modulated the magnitude of the brainstem response in the high load condition (i.e., $n = 3$). These findings supported a suggested model by which a late and central mechanism, namely WM, suppresses irrelevant sensory information at an early processing stage. Vogel, McCollough, and Machizawa (2005) also provided evidence to support the notion that individuals differ in their ability to control processes that regulate access to WM, by measuring contra-lateral delay activity (CDA) amplitude, which reflects the number of representations stored in WM. They showed that high capacity individuals, compared to low capacity, were more efficient at filtering out distractors. That is, participants with high capacity had smaller CDA amplitude when two of the four items to be maintained were distractors compared to the condition in which all four items were relevant. Compared to high capacity individuals, low capacity individuals showed lower filtering efficiency scores. The studies described here demonstrate that the demand to update the representation of the changing environment might be impaired as a result of the encoding and maintenance processes in WM.

A third mechanism by which WM load may impair a subsequent target detection is short term consolidation. This possibility holds that detection is not affected by the concurrent maintenance per se, but by central encoding and consolidation processes needed to support maintenance (Jolicoeur & Dell'Acqua, 1998; Vogel, Woodman, & Luck, 2006). Since these processes demand attention, detection would be impaired until they are completed. Previous work on short term consolidation demonstrated that this process is carried out serially, item by item, at a rate of 50–150 ms per item.

The studies reviewed here outline a connection between encoding and maintaining information and the ability to attend to new input. Still, a fourth possibility is that detection does not rely on WM, and hence would not be affected by manipulating WM load.

In light of this, the current study is aimed at examining whether WM load modulates target detection. A version of the change detection paradigm (Luck & Vogel, 1997) was used. In this paradigm, participants are briefly presented with a memory array of colored squares in changing locations and varied set-sizes. Following a short delay, one probe stimulus is presented and the participants are asked to indicate whether or not the probe is similar in color to the square that appeared in that location in the memory array. In the interval between the memory array and the test probe, participants have to maintain the colors and locations of the squares in WM in order to perform correctly. In this interval we introduced a target detection task. Specifically, a target stimulus was presented in some of the trials, and the participants were required to respond when they detect the target. The set-size of the memory array was also manipulated.

According to the previously reported findings we expected that larger memory arrays would lead to slower RTs in the target detection task, and that this interference would be larger when the target will be presented shortly after the presentation of the memory array, rather than closer to the probe presentation.

Five experiments are reported in this study. The first experiment explored the effect of WM load on ensuing target detection. The second experiment further established the effect of load on target detection, by using another (smaller) set-size which created a minimal load. The third experiment explored whether the effect of load on target detection is a result of encoding and memorizing processes in WM, or rather caused by the visual presentation of the memory array. The latter possibility was further examined in the fourth experiment, which compared the set-size effect in simultaneous and serial memory array presentations. The fifth experiment was designed to examine whether the effect of load on target detection is modality-specific, by using an auditory target rather than a visual one.

2. General method

2.1. Participants

A total of 110 students from Ben-Gurion University of the Negev participated in the study for partial course credit or monetary compensation. All participants had normal or corrected-to-normal vision and reported not having learning disabilities or neurological deficits. Experiment 1 involved nineteen participants (14 females, mean age: 22.8 years). One participant was excluded from the analysis due to exceptionally high error rates in the target detection task (26%) and low accuracy in the change detection task (41%). Experiment 2 involved eighteen participants (9 females, mean age: 24.4 years). Experiment 3 involved nineteen participants (15 females, mean age: 22.9 years). Experiment 4 included 36 participants (19 females, mean age: 25.1 years). Experiment 5 involved eighteen participants (12 females, mean age: 24.9 years). One participant was excluded due to an exceptionally high error rate in the target detection task (16%).

2.2. Apparatus

All experiments were run on a desktop computer with a 17-inch color screen monitor. The experiments were programmed in E-prime (Psychological Software Tools, Inc., Pittsburgh, PA). Responses were collected through the computer keyboard and a foot pedal connected to a serial response box (Psychology Software Tools, Inc., Pittsburgh, PA).

2.3. Stimuli

2.3.1. Memory array

The stimuli were presented within a $14.25° \times 14.25°$ area in the center of the screen against a gray background (assuming a 60 cm viewing distance). All set-sizes that were presented occupied the same area on the screen. Stimuli consisted of colored squares ($.95° \times .95°$) selected randomly from a set of 15 different discriminable colors.[1] Stimuli were placed randomly on the screen with the constraint that a given color could not appear more than twice within an array and that the distance between squares was at least 1.9 (center to center, both vertically and horizontally).

2.3.2. Test probe

The probe stimulus was a single, colored square ($.95° \times .95°$) appearing in a location that was occupied by a stimulus in the memory array.

2.3.3. Visual target

The stimulus was a hollow red equilateral triangle ($.76° \times .76°$) presented on gray background in randomly selected locations around the corners of the screen, outside the area in which the memory array was presented.

2.4. Procedure

A version of the change detection paradigm was used, with a detection task in the retention interval (see Fig. 1 for a typical trial). Participants were presented with an array of colored squares for 100 ms and were instructed to memorize their colors and locations. Set-sizes varied between one and eight (see below for differences between the experiments). All set-sizes appeared at a random order within a block. A retention interval of 2700 ms followed the memory array. In the retention interval a target was presented for 100 ms, with 70% probability

[1] Black, Maroon, Green, Olive, Navy, Purple, Teal, Red, Lime, Yellow, Blue, Magenta, Cyan, White, Orange. The probability of each color to appear in the memory array was equal in all set-sizes. Hence, the similarity between the *red* target and the *red* square in the memory array does not affect the set-size effect discussed later in this paper.