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Effects of working memory contents and perceptual load on distractor processing: When a response-related distractor is held in working memory

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ABSTRACT

Working memory and attention are closely related. Recent research has shown that working memory can be viewed as internally directed attention. Working memory can affect attention in at least two ways. One is the effect of working memory load on attention, and the other is the effect of working memory contents on attention. In the present study, an interaction between working memory contents and perceptual load in distractor processing was investigated. Participants performed a perceptual load task in a standard form in one condition (Single task). In the other condition, a response-related distractor was maintained in working memory, rather than presented in the same stimulus display as a target (Dual task). For the Dual task condition, a significant compatibility effect was found under high perceptual load; however, there was no compatibility effect under low perceptual load. These results suggest that the way the contents of working memory affect visual search depends on perceptual load.

1. Introduction

Working memory and attention are closely related to each other. Theories of working memory assume a role for attention in executive functions (e.g., Baddeley, 2012; Cowan, 2001), and many theories of attention claim that working memory is critically involved in controlling attention (e.g., Desimone & Duncan, 1995; Duncan & Humphreys, 1989; Treisman & Gelade, 1980; Wolfe, 1994). Recently, some researchers claimed that working memory is basically attention directed at internal representations (e.g., Awh & Jonides, 2001; Chun, Golomb, & Turk-Browne, 2011; Kiyonaga & Egner, 2013, 2014; Oberauer & Hein, 2012; Postle, 2006).

Working memory can affect attention in at least two ways: one is through working memory load, and the other is through working memory content. Effects of working memory load on attention are concerned with the limitation of processing resources. When we have to perform an attention task while we hold some items in our memory, our attentional resources are reduced, resulting in performance impairments. For example, working memory load tends to increase distractor interference in the flanker task (e.g., Ahmed & de Fockert, 2012; Caparos & Linnell, 2010; Lavie, Hirst, de Fockert, & Viding, 2004). Working memory load has also been shown to increase Stroop interference (e.g., Stins, Vosse, Boomsma, & de Geus, 2004), and spatial working memory load can impair performance in visual search (e.g., Oh & Kim, 2004; Woodman & Luck, 2004).

Working memory contents have been shown to affect attentional capture (e.g., Awh, Jonides, & Reuter-Lorenz, 1998; Downing, 2000; Kiyonaga & Egner, 2014; Olivers, Peters, Houtkamp, & Roelfsema, 2011; Pashler & Shiu, 1999; Soto & Humphreys, 2007; Woodman & Luck, 2007). In this case, participants are typically asked to hold one item in working memory while they perform an attention task. For example, Awh et al. (1998) asked participants to remember the location of a letter, followed by a shape discrimination task. Performance on the shape discrimination task was better when the shape was presented at the memory location. They concluded that the locations maintained in spatial working memory received continuous attention.

Kiyonaga and Egner (2014) used a Stroop task to examine whether working memory and attention draw on the same attentional resources and operate over the same representations. Participants were asked to remember a colour word, then to name the colour of a patch. Response times were shorter when the colour that was stored in working memory was the same as the colour of the patch, as is found in the classic Stroop interference effect. The results of these studies suggest that working memory contents affect attentional guidance.

With regard to measuring levels of distractor processing, a perceptual load task (e.g., Lavie, 1995; Lavie, 2005; Lavie & Tsal, 1994) is one of the most commonly used paradigms. In the perceptual load paradigm, participants are required to discriminate between two target stimuli (e.g., N and X) in a multi-element display. The task uses a variation of the Eriksen flanker task (Eriksen & Eriksen, 1974), in which a target

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and response-related distractor (either compatible or incompatible) are presented with a number of response-unrelated distractors. The response-related distractor is either the same as the target (compatible) or the same as the alternative item associated with a different response (incompatible), and the response-related distractor is typically specified by spatial separation. Perceptual load is typically manipulated with the heterogeneity of response-unrelated distractors (e.g., Lavie, 1995; Lavie & Tsal, 1994) or with distractor Set size (e.g., Lavie & Cox, 1997). With the heterogeneity manipulation, perceptual load is low when the distractors are homogeneous, and it is high when they are heterogeneous. With the Set size manipulation, perceptual load is low when distractor Set size is small, whereas perceptual load is high when Set size is large. A compatibility effect is a measure of distractor interference, and is calculated by the reaction time difference between responses in the Incompatible and Compatible conditions. The perceptual load theory claims that when perceptual load is low, attentional resources spill over to process the response-related distractor, resulting in a compatibility effect (late selection). However, when perceptual load is high, attentional resources are fully consumed by target processing, and as a result, the distractors are not processed, resulting in no compatibility effect (early selection).

The perceptual load theory claims that perceptual load contributes to attentional selection, even though its mechanism is still being debated (e.g., Tsal & Benoni, 2010; Wilson, Muroi, & MacLeod, 2011). For example, stimulus saliency, such as abrupt onsets and feature singletons, might also play significant roles in perceptual selection (e.g., Biggs & Gibson, 2010, 2014; de Fockert, 2013; Eltiti, Wallace, & Fox, 2005; Gibson & Bryant, 2008; Theeuwes & Burger, 1998). It is also possible that distractor processing is affected by other factors. For example, Tellinghuisen and Nowak (2003) used an auditory distractor in perceptual load tasks and found distractor interference in the high perceptual load condition. They concluded that auditory distractors are processed regardless of visual perceptual load, but the compatibility effect was obtained only for high perceptual load because the ability to inhibit the cross-modal effect from auditory distractors is reduced under high perceptual load.

Lavie et al. (2004) extended the perceptual load model to include effects of working memory load on distractor processing. They manipulated working memory load (High vs. low) and perceptual load (High vs. low), and showed that perceptual load decreased distractor interference whereas working memory load increased distractor processing. They claimed that perceptual load decreased distractor interference because high perceptual load reduced distractor information entering into the working memory system that is responsible for the control of responses. On the other hand, working memory load limits the amount of attentional resources available for resolution of distractor interference; and therefore, high working memory load increases distractor interference.

However, this interaction between working memory load and perceptual load depends on the modality of information. For example, in a previous study (Koshino & Olid, 2015), we found that effects of working memory load on distractor processing in perceptual load displays depend on the modality of information in working memory. In a letter discrimination task (N vs. X), verbal working memory load affected distractor processing, but visual working memory load did not (see also Kim, Kim, & Chun, 2005; Park, Kim, & Chun, 2007). Konstantinou and Lavie (2013) and Konstantinou, Beal, King, and Lavie (2014) also showed dissociation between different types of working memory load. Visual Short Term memory (VSTM) load and perceptual load decreased distractor processing. On the other hand, working memory load such as letter memory load increased distractor processing.

One important question that remains to be addressed concerns the effects of working memory contents and perceptual load on distractor processing. The question of content concerns the *prior* presence or absence of the distractor in working memory, rather than in the visual display. As discussed above, the perceptual load hypothesis claims that for the low perceptual load condition, attentional resources spill over to process distractor information resulting in competition for the control of responses between target and distractor information in working memory. However, under high perceptual load, most attentional resources are consumed in perceptual processing; and therefore, the response-related distractor is not processed, resulting in no distractor interference. Therefore, it follows from the perceptual load hypothesis that if distractor information *already* exists in working memory, it should interfere with target processing even when perceptual load is high. Therefore, in the present study, it was hypothesized that distractor interference would be observed for high perceptual load if the response-related distractor is maintained in working memory. In Lavie's original perceptual load model, there were two ways to manipulate perceptual load. One was stimulus heterogeneity (e.g., Lavie, 1995; Lavie & Tsal, 1994), and the other was Set size manipulation (e.g., Lavie & Cox, 1997). Therefore, in the present study, these two types of perceptual load are manipulated. Stimulus heterogeneity is manipulated for perceptual load in Experiment 1, and stimulus heterogeneity and Set size are manipulated for perceptual load in Experiment 2.

2. Experiment 1

2.1. Methods

2.1.1. Participants

Fourteen students from California State University, San Bernardino, participated for course credits. They all had normal or corrected to normal vision and gave informed consent that was approved by the Institutional Review Board.

2.1.2. Stimuli

There were Single task and Dual task conditions. The Single task was a typical perceptual load task without any memory component, in which participants were asked to find a target (N or X). Set size was fixed at six items consisting of a target and five response-unrelated distractors. Stimulus items were arranged in a circular fashion around a central fixation point. An extra response-related distractor was presented 5 cm (4.6°) to the right of the imaginary circle around the fixation point, and was either the same as the target (compatible) or the same as the alternative target (incompatible) for the Single task. For the perceptual load manipulation, the low Heterogeneity condition included homogeneous distractors (all Os), whereas a high Heterogeneity condition contained heterogeneous distractors (e.g., K, T, V, Y, Z). In the Dual task condition, a response-related distractor was presented as a memory item before visual search, and a visual search display contained only six items without the response-related distractor. From a viewing distance of approximately 60 cm, the letters measured 0.8 cm (0.76°) in height and 0.5 cm (0.48°) in width, and the radius of the imaginary circle was 2.8 cm (2.67°). The letters were black against a grey background. The memory item and the probe item were placed 1.4 cm (1.34°) above the fixation point. The stimuli were presented on a 17-in monitor controlled by a Pentium computer using E-Prime version 1.1 (Psychology Software Tools).

2.1.3. Procedure

The experiment took place in a dimly lit room. For the Single task condition, a central fixation point appeared for 500 ms at the beginning of each trial. Then a visual search display was presented. Participants were asked to press "n" key with their right index finger for the target "N", and "x" key with the left index finger for the target "X". The display stayed on until the participants made a response or for 2000 ms, whichever occurred first. For the Dual task condition, following the central fixation point, a memory item (response-related distractor) was presented above the fixation point for 250 ms followed by a mask at the same location consisting of three #s for 250 ms, followed by a visual search display. After participants made a response to the visual search display, a