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Precision requirements do not affect the allocation of visual working memory capacity

Xu He[a], Weiwei Zhang[b], Cuihong Li[a], Chunyan Guo[a,*]

[a]Beijing Key Laboratory of Learning and Cognition, Department of Psychology, Capital Normal University, Beijing 100048, PR China
[b]Department of Psychology, University of California, Riverside, CA 92521, USA

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ABSTRACT

There has been a debate about whether allocation of visual working memory (VWM) capacity was flexible. One of the key points about this issue is whether complexity has an effect on the capacity, and one of the critical features of complex objects is higher requirements on the encoding precision than simple objects. Thus we investigated the influence of precision requirements on the allocation of VWM capacity resources, by comparing VWM capacity under different levels of sample-test similarity in a change-detection task. If the VWM capacity is limited by a fixed number of items, then the capacity should not be affected by precision requirements; however, if the capacity is allocated flexibly, then precision requirements should influence the capacity. Cowan's *K* and amplitude of contralateral delay activity (CDA) were used as behavioral and neurophysiological measures of VWM capacity, respectively. Cowan's *K* for high-precision discrimination was calculated on the basis of the accuracy of a small number of large-change trials inserted into high-precision blocks. This approach avoided the confounder of different test-phase difficulties between the low- and high-precision conditions and controlled for errors during the test phase. The results showed no effect of precision requirements on VWM capacity. However, analysis of the late positive component (LPC) amplitude indicated that higher precision requirements indeed caused more top-down control over VWM retention. These results support the hypothesis that VWM is limited by a fixed number of items.

1. Introduction

Working memory, as the core of cognition, can retain and manipulate only limited amounts of information simultaneously. Researchers continue to debate how the limited resources of the visual working memory (VWM) capacity are allocated. Slot models propose that the resources are allocated in a discrete manner, and capacity is limited to 3–4 items (Anderson et al., 2011; Luck and Vogel, 1997; Zhang and Luck, 2008). According to this viewpoint, the resolution of each item is fixed, and the capacity is not affected by task requirements related to the precision of representation (or so-called "precision requirements"). In contrast, flexible resource models argue that although the total amount of resources is limited, the number of items that

*Corresponding author. Fax: +86 10 68902413.
E-mail addresses: explorer.hx2012@gmail.com (X. He), guocy@cnu.edu.cn (C. Guo).

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can be stored is not limited, because capacity resources can be flexibly distributed to each item in a continuous manner (Bays and Husain, 2008; Fukuda et al., 2010; Wilken and Ma, 2004).

On the issue about allocation of capacity, there is a dispute about the effect of complexity of objects on working memory capacity, outside the core debate between the two classes of theories of VWM capacity. One view is that increased complexity will lead to lower capacity, because more resources need to be allocated to form a specific representation of a complex object. Supports come from studies where working memory performance was worse for complex than for simple objects (Alvarez and Cavanagh, 2004; Gao et al., 2009; Luria et al., 2010; Wheeler and Treisman, 2002). For example, Alvarez and Cavanagh (2004) demonstrated that VWM capacity decreased as the object complexity increased, e.g., from a capacity of 4 for colored squares to approximately 1.6 for shaded cubes.

However, Awh et al. (2007) questioned this conclusion, because complexity often accompanies sample-test similarity. That is, as the complexity of an object increases, there is a corresponding increase in sample-test similarity, which leads to more errors when the sample and test are compared (Awh et al., 2007). To test this possibility, Awh et al. (2007) compared accuracy for within-category (high-similarity) and cross-category (low-similarity) change detection of complex objects such as Chinese characters and cubes. For within-category changes, accuracy decreases as complexity increases; however for cross-category changes, the accuracy and capacity estimates were similar between complex and simple objects (e.g., color squares). Thus, the decreased accuracy for complex objects may result from increased difficulty in comparing the sample and test, due to the higher sample-test similarity for complex objects. Increased sample-test similarity for complex objects leads to higher demand on encoding precision of representation (which we called as higher ‘precision requirements’) to ensure accurate discrimination between the changed item and the corresponding sample item. Therefore, the results by Awh et al. indicate that high-precision requirements impair accuracy, but not capacity.

A caveat in Awh et al. (2007) study is that participants can rely on partial features of complex objects to perform the change-detection task correctly. By remembering only common features of the category, participants could respond correctly to cross-category changes (because of the pronounced distinctions between the stimulus categories) but not to with-category changes. According to this possibility, the experimental manipulation of encoding precision with sample-test similarity would be ineffective. Encoding precision can be manipulated more reliably when the stimuli to be remembered are simple unidimensional features, such as colors (Luck and Vogel, 2013). Zhang and Luck (2011) instructed participants to retain colors in their working memory, and used a behavioral method that could measure capacity and precision independently. They found that participants could not increase capacity by decreasing encoding precision when this trade-off was required in the task.

Measuring electroencephalographic (EEG) data of the contralateral delay activity (CDA) is one method used to observe the allocation of capacity resources during VWM retention, while ensuring that effects from the test phase do not influence the results. The CDA is a large negative-going voltage in the hemisphere contralateral to the memorized hemifield during the delay period, and its amplitude is often measured as the differential activity between the ipsilateral and contralateral waveforms (Vogel and Machizawa, 2004). The CDA is widely used as a neural index of the number of retained items, because its amplitude increases with the memory set size and reaches an asymptote at the working memory capacity (Ikkai et al., 2010; McCollough et al., 2007; Vogel and Machizawa, 2004). Besides, the CDA has been found to be sensitive to complexity of memorized objects as well (Gao et al., 2009; Luria et al., 2010). More complex objects induced greater CDA amplitude, when the number of items was identical. Thus, the CDA appears to be an index of working memory allocation rather than the number of retained items. As CDA is measured before the test phase, it is a more efficient indicator than behavioral index to indicate VWM capacity without the effect from test-phase difficulty.

However, no conclusion has been reached regarding whether the CDA is sensitive to the encoding precision required by the task. By analyzing the CDA amplitude while manipulating the demand on the encoding precision of simple stimuli, recent studies found discrepancies in the relationship between precision requirements and the allocation of capacity resources indexed by the CDA amplitude. For example, by asking participants to remember the orientation of bars, Machizawa et al. (2012) showed that VWM precision could be willfully increased with increasing precision requirements at a low set size, and that increased precision led to a higher CDA amplitude. In contrast, Luria et al. (2010) asked participants to remember colors and found that precision requirements did not affect the CDA amplitude. One problem with Luria et al. (2010) is that they manipulated the sample-test similarity, but the influence of inter-item similarity within sample array was confused, as similarity within sample array was not identical between low- and high-similarity conditions.

Different levels of working memory loads are often coupled with different levels of demands for internal attentional controls from the prefrontal cortex (PFC). Consistent with the critical roles of the PFC in exerting top-down control for working memory storage within posterior regions (McNab and Klingberg, 2008; Roggeman et al., 2013; Voytek and Knight, 2010), the late positive component (LPC) over the PFC appears to be related to the maintenance of working memory (Gao et al., 2011; Kusak et al., 2000; Li et al., 2006). Specifically, Gao et al. (2011) observed that the LPC amplitude increased with the number of items retained in working memory.

Considering the conflicting results regarding the relationship between precision requirements and capacity from both behavioral and event-related potential (ERP) studies (Machizawa et al., 2012; Luria et al., 2010; Zhang and Luck, 2011), we assessed the effect of precision requirements on VWM capacity by manipulating the sample-test similarity of a change-detection task. To avoid the possibility that participants would remember partial features, we focused on the working memory of colors. We manipulated the demand on working memory encoding precision by using two levels of sample-test similarity: a high-precision condition with high sample-test similarity and a low-precision condition with low sample-test similarity. In Experiment 1, in order to compare the capacity for the two conditions with identical difficulty of the test phase, a small number of large-change trials were mixed into high-precision blocks (with