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Resources masquerading as slots: Flexible allocation of visual working memory ☆

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ABSTRACT

Whether the capacity of visual working memory is better characterized by an item-based or a resource-based account continues to be keenly debated. Here, we propose that visual working memory is a flexible resource that is sometimes deployed in a slot-like manner. We develop a computational model that can either encode all items in a memory set, or encode only a subset of those items. A fixed-capacity mnemonic resource is divided among the items in memory. When fewer items are encoded, they are each remembered with higher fidelity, but at the cost of having to rely on an explicit guessing process when probed about an item that is not in memory. We use the new model to test the prediction that participants will more often encode the entire set of items when the demands on memory are predictable.

1. Introduction

Whether the capacity of visual working memory is better characterized as a limited number of discrete slots or as a continuous resource is a source of ongoing debate (Luck & Vogel, 2013; Ma, Husain, & Bays, 2014). According to the slots view, a limited number of items are stored with high precision (Luck & Vogel, 1997). Resource-based accounts rather propose that memory can be allocated more

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flexibly among items, with no necessary constraint on the number of items that can be held in memory (Wilken & Ma, 2004).

The change-detection task has long been used to understand the capacity of visual working memory (Cowan, 2001; Luck & Vogel, 1997; Pashler, 1988; Phillips, 1974). In a change detection task, observers are presented with an array of items to remember followed by a test array given a short period later. Observers are asked to determine whether the study and test arrays are the same, or if they have changed. In their seminal paper, Luck and Vogel (1997) showed that performance suffered a steep drop-off in performance once participants had to remember more than about 3–4 items. A slots-based account of this data proposes that the capacity of memory is around 3–4 items, and performance worsens once this capacity is exceeded (Awh, Barton, & Vogel, 2007; Barton, Ester, & Awh, 2009; Vogel, Woodman, & Luck, 2001).

Rouder et al. (2008) found explicit evidence for a slots model account of choice probability data in change detection tasks. In their study, the proportion of correct change responses (hits) and incorrect change responses (false alarms) were plotted using receiver operating characteristic (ROC) curves. Rouder et al. (2008) proposed a high-threshold version of a slots model, which assumed that items in memory were stored with enough precision that change/same discrimination for remembered items is perfect. Such a model has been long known to predict straight-line ROC curves (Green & Swets, 1966). Human performance in their experiment was well captured by this slots model, which outperformed a signal detection model representing the class of resource-based models.

Donkin, Tran, and Nosofsky (2014) replicated the results from Rouder et al. (2008). They also showed that the slots model was preferred in an experiment featuring a more stringent bias manipulation, providing a stronger test of the slots model's predictions. Donkin, Nosofsky, Gold, and Shiffrin (2013) also developed slots and resource models that account for both choice proportion and response time data, and showed that data from the Rouder et al. (2008) paradigm are better characterized by slots models.

However, some of the data from change-detection tasks have been shown to be more consistent with a resource-based account of capacity. For example, Keshvari, Van den Berg, and Ma (2013) showed that resource models outperformed slots models in a change-detection task. Further, Van Den Berg, Ma, and colleagues have repeatedly demonstrated that a particular type of resource-based model, one that assumes a flexible and stochastic allocation of memory, consistently outperforms traditional slot-based models in other visual working memory paradigms (e.g., Van den Berg, Awh, & Ma, 2014; Van den Berg, Shin, Chou, George, & Ma, 2012).

The literature on the capacity of visual working memory is inconsistent, with evidence that supports both slot-like and resource-like capacity. Our aim here is to provide a potential resolution to why we see evidence for both slots and resource models. We begin by noting that although resource models can mimic slots models (by allocating memory to only some of the items in the display), slots models are unable to mimic resource models.[1] As such, one is forced to conclude that visual working memory is a flexible resource. However, we propose that the flexible resource of working memory is allocated in a slot-like fashion in certain environments.

We now pursue our conjecture that in certain environments, the resource-based capacity of memory is allocated such that it appears to be slots-based. We first describe the series of previous experiments that led us to this proposition, and outline a pair of new experiments that test our prediction. We then introduce a new flexible-resource computational model that incorporates both slot-like and resource-like encoding of items; either dividing its memory among all of the items in a display, or encoding a smaller subset of items (but with higher resolution). We show that under different environments, participants do indeed show more or less slot-like encoding of stimuli.

1.1. Old experiments: why we think that certain environments lead to slot-like encoding

Donkin et al. (2014) replicated and extended the results from Rouder et al. (2008) across a series of four experiments. All experiments used the change detection task, but differed in the exact manipulation of two primary independent variables; set size and change proportion. As set size – the number

[1] Note that the slots + averaging model in Zhang and Luck (2008) can mimic resource models when the number of items to remember is smaller than capacity, because a single item can be stored in multiple slots, thus improving its resolution in memory.