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Response-time evidence for mixed memory states in a sequential-presentation change-detection task

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ABSTRACT

Response-time (RT) and choice-probability data were obtained in a rapid visual sequential-presentation change-detection task in which memory set size, study-test lag, and objective change probabilities were manipulated. False "change" judgments increased dramatically with increasing lag, consistent with the idea that study items with long lags were ejected from a discrete-slots buffer. Error RTs were nearly invariant with set size and lag, consistent with the idea that the errors were produced by a stimulus-independent guessing process. The patterns of error and RT data could not be explained in terms of encoding limitations, but were consistent with the hypothesis that long retention lags produced a zero-stimulus-information state that required guessing. Formal modeling of the change-detection RT and error data pointed toward a hybrid model of visual working memory. The hybrid model assumed mixed states involving a combination of memory and guessing, but with higher memory resolution for items with shorter retention lags. The work raises new questions concerning the nature of the memory representations that are produced across the closely related tasks of change detection and visual memory search.

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1. Introduction

Visual working memory (VWM) is the short-term memory system that maintains representations of visual inputs. The nature of VWM is often investigated by presenting observers with brief visual displays and then testing the observers' memory for objects from different locations of the displays. A fundamental result is that VWM is highly limited in its capacity: As the number of to-be-remembered objects increases, the observer's ability to remember individual objects within the display gets worse.

A longstanding theoretical debate concerns the underlying basis for this limited capacity. According to the "discrete-slots" view (e.g., Awh, Barton, & Vogel, 2007; Barton, Ester, & Awh, 2009; Cowan, 2001; Luck & Vogel, 1997, 2013; Pashler, 1988; Rouder et al., 2008; Vogel, Woodman, & Luck, 2006), VWM makes available some number of slots for storing to-be-remembered items. The slot-based memories are conceptualized as being all-or-none: When memory is probed, if the test item occupies one of the slots, then the observer can judge its presence with no loss in resolution, regardless of the number of other items in the set of to-be-remembered objects. By contrast, if the object has not been stored in one of the discrete slots, then there is a complete loss of resolution. That is, no information about the presented object remains and the observer is forced to guess with regard to its identity. Although there are various versions of the discrete-slots view, the key aspect that we emphasize in this article is that the process gives rise to *mixed states* of memory: responding is presumed to reflect a mixture of memory-based responding and "zero-stimulus-information" responding that requires guessing.

An alternative view proposes that VWM consists of a pool of resources that is allocated in continuous fashion through sharing of the resources (e.g., Alvarez & Cavanagh, 2004; Bays, Catalao, & Husain, 2009; Bays, Gorgoraptis, Wee, Marshall, & Husain, 2011; Bays & Husain, 2008; Keshvari, van den Berg, & Ma, 2013; Ma, Husain, & Bays, 2014; van den Berg, Shin, Chou, George, & Ma, 2012; Wilken & Ma, 2004). Thus, if the number of memory items is small, then the observer can maintain high-resolution representations of all of them. By contrast, if a large number of items must be maintained, then the continuous sharing of resources leads the observer to have lower-resolution representations of the individual items. Again, there are wide varieties of shared-resources models. The key aspect that we emphasize in this article is that the process gives rise to *continuously varying* states of memory with at least partial information retained for all to-be-remembered objects. Except for very occasional spurious trials involving inattention, there is no "zero-information" state that requires a true guessing process.

Finally, a variety of hybrid models have also been proposed that combine key elements of the discrete-slots and shared-resources approaches (e.g., Cowan & Rouder, 2009; Sims, Jacobs, & Knill, 2012; Zhang & Luck, 2008). Furthermore, various forms of evidence suggest that item limits and resource limits may be mediated by separate neural and cognitive systems (e.g., Awh et al., 2007; Unsworth, Fukuda, Awh, & Vogel, 2014; Xu & Chun, 2006).

These different views have led to an extensive and influential debate about the properties of VWM. Perhaps the most dominant modern paradigms used for contrasting the theories are "continuous recall" paradigms (Wilken & Ma, 2004; Zhang & Luck, 2008). In these paradigms, observers attempt to recall and reproduce a continuous value from a probed location of a briefly studied visual display (e.g., the color of a square). The discrete-slots models predict that the distribution of reproduced values is a mixture of responses from VWM and components that are purely guessing. In contrast, strong versions of the shared resource models predict that a single-component distribution becomes more diffuse as VWM resources are increasingly taxed.

The continuous-recall paradigms have yielded important insights. However, there are also some limitations associated with the approach. One limitation is that the properties of the paradigm itself may interfere with the information stored in VWM. For example, in the typical version of the paradigm, the response is produced by indicating a location along a continuous-valued response device. Note that presentation of the device itself (in which all continuous values are simultaneously present) may be highly interfering of the original memory, thereby leading to underestimates of the amount of information that was immediately available when memory was probed (e.g., Souza, Rerko, Lin, &