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The mechanisms of working memory capacity: Primary memory, secondary memory, and attention control

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ABSTRACT

Working memory capacity is traditionally treated as a unitary construct that can be explained using one cognitive mechanism (e.g., storage, attention control). Several recent studies have, however, demonstrated that multiple mechanisms are needed to explain individual differences in working memory capacity. The present study focuses on three such mechanisms: Maintenance/disengagement in primary memory, retrieval from secondary memory, and attention control. Structural equation modeling reveals that each of these mechanisms is important to explaining individual differences in working memory capacity. Further analyses reveal that the degree to which these mechanisms are apparent may be driven by the type of task used to operationalize working memory capacity. Specifically, complex span (processing and storage) and visual arrays (change detection) performance is strongly related to a person's attention control, while running memory span (memory for last n items on a list) performance has a relationship to primary memory that is apparent above-and-beyond other working memory tasks. Finally, regardless of the working memory task that is used, it is found that primary and secondary memory fully explain the relationship of working memory capacity to general fluid intelligence.

....working memory is not a memory system in itself, but a system for attention to memory....

Oberauer et al. (2007)

Introduction

Working memory is the cognitive system that allows people to retain access to a limited amount of information, in the service of complex cognition. More succinctly, as stated above, working memory allows people to attend to goal-relevant memories. Critically, individual differences in working memory capacity are associated with performance in diverse aspects of cognition, such as multi-tasking (Hambrick, Oswald, Darowski, Rench, & Brou, 2010), emotion regulation (Kleider, Parrott, & King, 2009), hindsight bias (Calvillo, 2012), and susceptibility to stereotype threat (Hutchison, Smith, & Ferris, 2012). Perhaps most famously, working memory capacity shares at least half its statistical variance with general fluid intelligence (the ability to reason with novel information; Kane, Hambrick, & Conway, 2005). Thus, exploring the mechanisms of working memory capacity may provide the most straightforward method of clarifying the processes involved in human reasoning (Conway, Getz, Macnamara, & Engel de Abreu, 2010; Oberauer, Schulze, Wilhelm, & Süß, 2005). We highlight three broadly

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defined mechanisms that are prevalent in the literature: Primary memory, attention control, and retrieval from secondary memory.

Primary memory

As it relates to working memory, primary memory is typically construed as a type of limited capacity storage that can maintain 3–5 items at any one point in time (Cowan, 2001; Luck & Vogel, 1997; Rouder, Morey, Morey, & Cowan, 2011; Unsworth & Engle, 2007b). In effect, it represents the size of a person's attentional focus (e.g., Cowan et al., 2005; Unsworth & Engle, 2007b). The function of this system is to protect relevant information from proactive interference (Cowan, 2001) and allow novel connections to be formed between disparate units of information (Oberauer et al., 2007).

While most theories of working memory capacity postulate that primary memory is a critical component, the assumption that this system strictly reflects multi-item storage is not universal. For instance, focal attention has also been researched as a serial process (e.g., Garavan, 1998; McElree, 2001; Verhaeghen & Basak, 2005), leading some to conclude that the primary memory aspects of working memory are better construed as a binding-function, than as a storage system. Specifically, the 3–5 item maintenance capacity is sometimes interpreted as a person's ability to form and break temporary associations between disparate memory units (Oberauer, 2002; Oberauer et al., 2007). These *bindings* provide facilitated access between contextually relevant units of memory. From this perspective, the size of a person's primary memory is determined by the efficacy with which new bindings are created and dissolved as the context of a situation changes. The present study was not designed to test between absolute-maintenance or binding-capacity theories; however, both perspectives will be examined when considering the implications of our results.

Attention control

Working memory capacity is typically operationalized via information that is either in conscious awareness, or can be readily recalled into awareness. Thus, it is parsimonious to equate working memory capacity with primary memory. However, the environment in which working memory operates may contain any number of distractions to which attention is drawn. The ability to select goal-relevant information and responses is therefore critical when the environment (or a memory search) activates conflicting information or prepotent responses.

In contrast to strict maintenance-related perspectives of working memory capacity (e.g., Colom, Abad, Quiroga, Shih, & Flores-Mendoza, 2008), the executive attention account (Engle, 2002) equates working memory capacity with the ability to use attention to select relevant information from the environment and to retain access to memories that reside outside of conscious awareness (Kane, Conway, Hambrick, & Engle, 2007). That is, working memory capacity is seen to be driven by ability to focus on critical information and resist having one's attention captured by distraction. Indeed, individual differences in working memory capacity are positively correlated to performance on a variety of attention capture tasks (Engle, 2002; Fukuda & Vogel, 2009, 2011; Hutchison, 2007; Kane, Conway, et al., 2007; Unsworth & Spillers, 2010). These tasks require test takers to make goal-relevant responses (e.g., look away from a peripheral flash) in the face of prepotent tendencies (e.g., the reflexive inclination to orient toward peripheral events; Engle, 2002). Critically, the information load for attention capture tasks is typically low (Roberts, Hager, & Heron, 1994), implying that the relationship between working memory capacity and resistance to attention capture is not readily explained by individual differences in temporary storage capacity.

Secondary memory

The previously discussed perspectives of working memory capacity focus on mechanisms of maintenance. Yet, it is noteworthy that many working memory tasks require test-takers to manage more information than the 3–5 units to which immediate awareness is constrained. Thus, regardless of the scope of a person's primary memory, or attention control abilities, some to-be-remembered information is likely to be displaced and therefore require retrieval from longer-term storage (Unsworth & Engle, 2007b).

For instance, Unsworth and Engle's (2007) dual-component model defines working memory capacity as a combination of limited-capacity maintenance in primary memory, as well as retrieval from *secondary memory*. Specifically, secondary memory is contextually-relevant information that is not currently maintained by primary memory. The critical variable is the specificity with which this information is searched. People who can constrain their searches of secondary memory on the basis of highly relevant cues (e.g., time periods, associated information) generate relatively few irrelevant retrieval candidates. In other words, little proactive interference is produced and critical information is recalled with a higher probability. In contrast, people who have difficulty selecting relevant cues will conduct relatively diffuse searches of secondary memory and thus will generate many irrelevant retrieval candidates. In other words they will contend with a high level of proactive interference and thus have a reduced likelihood of recalling critical information (see also Watkins, 1979; Wixted & Rohrer, 1994).

Working memory tasks

Working memory capacity can be measured through a variety of tasks that make a variety of demands on the system. It is therefore understandable if different working memory tasks reflect different mechanisms of working memory, and thus provide slightly different perspectives on the cognitive processes that define this construct. The present study focuses on working memory capacity as it is reflected in complex span, running memory span and visual arrays performance. Of particular importance, these tasks differ greatly in their demands, yet they predict reasonably similar variation in working memory capacity (Broadway & Engle, 2010; Cowan et al., 2005; Shipstead