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Towards an integrative model of visual short-term memory maintenance: Evidence from the effects of attentional control, load, decay, and their interactions in childhood

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ABSTRACT

Over the past decades there has been a surge of research aiming to shed light on the nature of capacity limits to visual short-term memory (VSTM). However, an integrative account of this evidence is currently missing. We argue that investigating parameters constraining VSTM in childhood suggests a novel integrative model of VSTM maintenance, and that this in turn informs mechanisms of VSTM maintenance in adulthood. Over 3 experiments with 7-year-olds and young adults (total N = 206), we provide evidence for multiple cognitive processes interacting to constrain VSTM performance. While age-related increases in storage capacity are undisputable, we replicate the finding that attentional processes control what information will be encoded and maintained in VSTM in the face of increased competition. Therefore, a central process to the current model is attentional refreshment, a mechanism that it is thought to reactivate and strengthen the signal of the visual representations. Critically, here we also show that attentional influences on VSTM are further constrained by additional factors, traditionally studied to the exclusion of each other, such as memory load and temporal decay. We propose that these processes work synergistically in an elegant manner to capture the adult-end state, whereas their less refined efficiency and modulations in childhood account for the smaller VSTM capacity that 7-year-olds demonstrate compared to older individuals. We conclude that going beyond the investigation of single cognitive mechanisms, to their interactions, holds the promise to understand both developing and fully developed maintenance in VSTM.

1. Introduction

Visual short-term memory (VSTM)[1] is a limited-resource system that allows the on-line storage and temporary maintenance of visual information, so that other cognitive processes can access and operate on it. Therefore, VSTM is vital to a broad range of cognitive abilities, e.g., it is correlated with fluid intelligence (e.g., Ackerman, Beier, & Boyle, 2002; Burgess, Gray, Conway, & Braver, 2011; Conway, Kane, & Engle, 2003; Cowan, Fristoe, Elliott, Brunner, & Saults, 2006; Engel de Abreu, Conway, & Gathercole, 2010; Engle, Tuholski, Laughlin, & Conway, 1999; Kane, Hambrick, & Conway, 2005; Kane et al., 2004) and it is involved in early learning and academic achievement (e.g., Amso & Johnson, 2006; Bull & Scerif, 2001; Cowan et al., 2005; Hitch, Towse, & Hutton, 2001; St Clair-Thompson & Gathercole, 2006; Stevens & Bavelier, 2012). Given its significance, a central topic of investigation across the cognitive sciences, for almost half a century now, has been the nature of VSTM, its core capacity limits, and its underlying neurocognitive mechanisms, although early conceptions date back to the 19th century (e.g., Williams, 1890).

An extensive and yet growing research body with adult and child populations has resulted in multiple accounts for memory maintenance and its constraints. These accounts range from pure storage capacity limitations (Cowan, 2001; Luck & Vogel, 1997) to decay (Barrouillet, Bernardin, & Camos, 2004; Burgess & Hitch, 1999; Ricker & Cowan, 2014; Towse, Hitch, & Hutton, 2000) and interference (Lewandowsky, Duncan, & Brown, 2004; Lewandowsky & Oberauer, 2009; Oberauer & Lewandowsky, 2008), both in the context of verbal short-term memory and VSTM. A noteworthy advancement in adult cognitive science is the recent emphasis on interactions between VSTM and selective attention (Awh, Vogel, & Oh, 2006; Chun, 2011; Chun & Turk-Browne, 2007;

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[1] With VSTM we refer to the capacity of individuals to maintain a small amount of information in mind for a short-term period. We note that in the literature this term has been used interchangeably with visual working memory (VWM, e.g., Cowan, 2001), even though the latter has specific connotations associated with dual processing tasks (e.g., Logie, 2011). However, to highlight that we do not use dual processing requirements here, and for consistency with our previous work, we use the former term, VSTM, throughout.

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Gazzaley, 2011; Gazzaley & Nobre, 2012; Nobre & Stokes, 2011; Postle, 2006; Stokes & Nobre, 2011), in an attempt to shed light on the nature and flexibility of VSTM. The contribution of selective attention has also started to gain ground in understanding development (as detailed in Section 1.4), but it remains debated (e.g., Cowan, Morey, AuBuchon, Zwilling, & Gilchrist, 2010) and has been treated mainly in isolation from other potential constraining mechanisms (e.g., Shimi, Nobre, Astle, & Scerif, 2014). This focus on isolated cognitive mechanisms is not warranted by the wealth of knowledge emerging from the field of developmental cognitive neuroscience: during development, improvement across multiple cognitive processes is associated with enhanced connectivity across networks (Fair et al., 2007; Solé-Padullés et al., 2016). Thus, it is theoretically counterproductive to attribute VSTM maintenance to a single mechanism without ruling out the contribution of other mechanisms through careful experimental control.

In the present study, we draw on both the adult and child literatures to integrate currently disparate accounts of VSTM maintenance. This attempt, we believe, highlights new directions that elucidate the nature of VSTM, its close interplay with attentional control from childhood, and most importantly the dynamic interplay of multiple non-mutually exclusive constraints on VSTM, in both the adult and child systems. We begin by overviewing the most influential models of WM, followed by a review of the current knowledge on the contribution of attentional control to VSTM for both the fully developed and developing systems. We then present three experiments with 7-year-olds and young adults investigating the effects of memory load and temporal decay on the interaction between attentional control and VSTM. We finally propose an integrative model, to offer a mechanistic description of the means by which attentional processes influence VSTM, and how these are further constrained by additional factors.

1.1. Theoretical models of short-term/working memory

VSTM is restricted in its capacity, i.e., recognised as a magic number 7 when studied with sequentially presented material (Miller, 1956) or limited to 4 items when studied with simultaneously presented materials (Cowan, 2001). Fundamental to preserving an efficient storage for adaptive behaviour have been the regulatory mechanisms gating access and keeping active in mind the information that is most relevant to current goals. A central role of attention is to select the information that is task-relevant and inhibit all else. Therefore, theoretical models of short- and working-memory (STM/WM) stipulate that attention controls the encoding of information into STM and its manipulation during maintenance in the form of executive processes (Baddeley, 2002b, 2003; Baddeley & Hitch, 1974; Cowan, 1999, 2005; Engle et al., 1999; Kane, Bleckley, Conway, & Engle, 2001; Kane et al., 2004). Specifically, the two most influential models of WM to date, proposed by Baddeley and Hitch (1974) and Cowan (1999) suggest distinct WM architectures, but both include an attentional component. According to Baddeley and colleagues (Baddeley & Hitch, 1974; Baddeley & Logie, 1999), WM involves a domain-general system, known as the *central executive*. This is an attentional system that regulates and acts upon two domain-specific systems, the *phonological loop* and the *visuo-spatial sketchpad*, that are specialised for the short-term storage of phonological and visual/spatial information respectively. The central executive is also responsible for co-ordinating the flow of information between the domain-specific systems and their communication with long-term memory (LTM) via the *episodic buffer* (Baddeley, 2000), a temporary storage system that is responsible for binding information originating from the two domain-specific systems and integrating them into chunks (Allen, Baddeley, & Hitch, 2006; Baddeley, Allen, & Hitch, 2011). Furthermore, the central executive is responsible for implementing a number of executive functions operating on the information stored in the domain-specific systems, such as attentional control (i.e., selecting incoming information), attentional focusing, attention switching, dual-task performance, and selecting and manipulating information in LTM (Baddeley, 1998, 2002a, 2002b, 2003; Baddeley & Hitch, 1974). Yet, the precise nature of the central executive remains somewhat elusive, as executive processes remain highly intercorrelated, albeit separable (Miyake et al., 2000). Furthermore, the original model does not offer a precise account of how these separable executive processes interact with the domain-specific systems (e.g., the visuo-spatial sketchpad) responsible for storage.

Cowan (1988, 2005, 2011), on the other hand, considers WM as an embedded-process within LTM, rather than a separate system. He proposes that WM represents a subset of LTM representations, such as physical and semantic item features and current thoughts, which are in an active state at any given instance. According to Cowan, a further subset of these active WM representations is considered to be in the *focus of attention*. Active representations are unlimited in number, but they are limited temporally as they are prone to decay and interference, whereas representations within the *focus of attention* are capacity limited to 3–5 chunks (Cowan, 1999, 2001), but are immune to decay and interference. In this unitary model of WM, the focus of attention refers broadly to processes involved in the active maintenance of stored representations in a limited capacity memory system, rather than to the control of information flow as it is the case for central executive. Oberauer (2002) extended Cowan's model by claiming that only a single item can reside within the *focus of attention* at any given moment (McElree, 2001, 2006; Oberauer & Bialkova, 2009 but see Gilchrist & Cowan, 2011).

While the two influential models above offer theoretical descriptions of a WM architecture (multicomponential vs. unitary respectively) and highlight a key role for attention in WM, both models exhibit limitations in providing mechanistic accounts of how attentional processes influence WM in the context of encoding and maintenance. For example, the multicomponential model (e.g., Baddeley & Hitch, 1974) does not detail precisely the encoding processes involved in WM, presumably because these operate on perceptual representations that fall within a cognitive domain that is distinguishable from memory. Nevertheless, this model explains the maintenance processes involved in STM by proposing on the one hand a verbal rehearsal mechanism maintaining the information stored in the phonological loop, and on the other an inner scribe mechanism maintaining the information in the visuo-spatial sketchpad (Logie, 1995, 2003, 2011). In contrast, the unitary model (e.g., Cowan, 1988) explains encoding in the context of activated features in LTM, but it has not tackled directly the mechanism (s) involved in actively maintaining the items in the focus of attention. Cowan (1992) proposed a memory scanning process of the items stored in STM that potentially keeps them in the focus of attention, but this process was studied only for verbal and sequentially presented material, leaving unexplored the specific maintenance mechanism responsible for visual and/or simultaneously presented material. Of note, it is essential for a comprehensive model of STM/WM to be able to account precisely for: (a) how domain-general processes such as selective attention interact with domain-specific systems, such as storage capacity for verbal and visuo-spatial material; and (b) how these factors influence different stages within the information processing stream, i.e., facilitating encoding and supporting maintenance. Understanding maintenance is especially important, because at any given moment our brain is required to resolve the competition arising from both external percepts and/or internal representations (Desimone & Duncan, 1995). Recent studies with both children and adults (see following sections) demonstrate that by understanding developmental similarities and differences in attentional influences on STM/WM, rich information about their dynamic relation emerges, ultimately fostering a better understanding of the basic mechanisms involved in VSTM/VWM.

1.2. Attentional contributions to VSTM in adulthood

It is now well-established that, in the adult system, attention and VSTM are closely intertwined (Chun & Turk-Browne, 2007; Corbetta,