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Individual differences in working memory capacity and long-term memory: The influence of intensity of attention to items at encoding as measured by pupil dilation

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ABSTRACT

The present study used pupil dilation as an index of the intensity of attention to determine if variation in attention at encoding partially accounts for the relation between working memory capacity (WMC) and long-term memory (LTM). In Experiment 1, participants completed a delayed free recall task while pupil dilation was simultaneously recorded. Results revealed high WMC individuals displayed an increase in pupil dilation across serial positions, whereas low WMC individuals exhibited a decline in pupil dilation. Experiment 2 employed a similar method but manipulated encoding conditions via value–directed remembering. Results demonstrated when later serial positions were labeled as more important, the pupillary response no longer declined for low WMC individuals. Instead, low WMC individuals increased attention across serial positions, with the caveat being that these individuals devoted less attention than high WMC individuals to all items under these conditions. Overall, results support the notion that high WMC individuals outperform low WMC individuals in delayed free recall, which is partly explained by the amount of attention devoted to items at encoding.

Introduction

Working memory (WM) is the ability to maintain and manipulate task relevant information in the presence of simultaneous processing and distraction (Baddeley & Hitch, 1974). WM is believed to encompass a resource limited system in which individuals can maintain approximately 4 ± 1 chunks of items (Cowan, 2001) in the current focus of attention and has been shown to predict a number of higher-order cognitive functions including reading and language comprehension (Daneman & Carpenter, 1980; Daneman & Merikle, 1996), general fluid intelligence (Ackerman, Beier, & Boyle, 2002; Engle, Tuholski, Laughlin, & Conway, 1999; Kyllonen & Christal, 1990), and of particular interest to the current study, the ability to successfully encode and retrieve information from long term memory (LTM; Unsworth, 2010, 2016; Unsworth, Brewer, & Spillers, 2009). While higher-order cognitive functioning in general is important for various reasons, our ability to successfully remember information is essential to everyday functioning. Not only does LTM performance partially explain the relation between working memory capacity (WMC) and general fluid intelligence (Unsworth et al., 2009; Unsworth, 2009a, 2010), but on a daily basis we are faced with the task of remembering an impending deadline, previously learned facts necessary for an exam or one's job, the name of an acquaintance, and more. As such, encoding and retrieving relevant information is a critical component of navigating the world around us. Given the importance of encoding and retrieval of relevant information, it is imperative that researchers better understand why some people (e.g., high WMC individuals) are better at remembering information than others. The present study sought to further address this question.

WMC and LTM

Research has demonstrated that high WMC and low WMC individuals differ in various aspects of LTM, including free (e.g., Unsworth, 2007) and cued (e.g., Unsworth, 2009b) recall. In prior work we have suggested a number of important reasons for these WMC related differences, including variation in overall search set size (i.e., search efficiency; Miller & Unsworth, in press; Unsworth, 2007; Unsworth & Engle, 2007) and variation in monitoring abilities (Unsworth & Brewer, 2010). Of note, these processes largely reflect control processes at retrieval. With respect to control processes at encoding, prior work suggests variation in encoding strategy use

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(Unsworth, 2016) may also account for some of the WMC-LTM relationship. It remains to be seen, however, whether other factors that influence the strength of memory representations in LTM could likewise account for some of the results discussed previously. Recovery of items from LTM is determined by an item's absolute strength (Rohrer, 1996); hence recovery is likely if the strength of an item exceeds some critical threshold. One factor that may influence the strength of recoverable items is the amount of attention that item receives at encoding, such that items that receive more attention at encoding may have greater strengths (see Unsworth, 2009a for related discussion).

Research consistent with this view (e.g., Anderson, Craik, & Naveh-Benjamin, 1998; Baddeley, Lewis, Eldridge, & Thomson, 1984) shows that dividing attention at encoding significantly impairs recall performance on a variety of LTM tasks, including free recall and paired-associates tasks. That is, when attention is not fully devoted to encoding items, those items are weakly encoded and chances of recovery are low. The notion that attention is important for encoding has also been used to explain levels of processing effects (see Craik & Lockhart, 1972). In these cases, it is not necessarily the amount of attention (or time spent attending to stimuli) that determines subsequent episodic memory. Rather, it is the elaborative nature of attentional processing at encoding. In either case, lower probability of recall may be attributed to items having lower recoverable strengths, which may be due to those items receiving less attentional processing at encoding. If individual differences in WMC are related to how much attention individuals allocate to items at encoding, this may be another mechanism responsible for recall accuracy findings that researchers (e.g., Unsworth, 2016; Unsworth & Brewer, 2010) commonly associate with search efficiency and monitoring processes.

In support of this claim, Kane and Engle (2000) showed that dividing attention at encoding impaired recall performance more so for high WMC individuals than for low WMC individuals, suggesting high WMC individuals engage in more attentional processing under normal learning conditions. What is more, substantial evidence exists demonstrating the importance of attentional factors in accounting for individual differences in WMC, particularly in terms of attention control (Engle & Kane, 2004). Therefore, it seems possible that individual differences in WMC could be related to differences in how much attention is allocated to items at encoding. The present study sought to address this possibility and to see whether differences in this aspect of attention control could partly explain high WMC individuals' greater recall accuracy. As such, the particular mechanism of interest in the present study is the intensity of attention devoted to items at encoding, which may be indexed via pupillometry.

Pupillary response as an index of attention at encoding

A great deal of prior research suggests that task evoked pupillary responses (TEPRs) reflect changes in pupil dilation relative to baseline levels due to the attentional demands imposed by a cognitive task (Beatty & Lucero-Wagoner, 2000; Goldinger & Papesh, 2012). For instance, the pupil dilates as math problem difficulty increases (Hess & Polt, 1964), as well as when memory load increases in traditional short term memory tasks (Kahneman & Beatty, 1966; Peavler, 1974). Research has further demonstrated that once memory load exceeds capacity limits, the pupillary response sometimes diminishes and displays a negative slope (Granholm, Asarnow, Sarkin, & Dykes, 1996; Granholm, Morris, Sarkin, Asarnow, & Jeste, 1997; Van Gerven, Paas, Van Merrienboer, & Schmidt, 2004), which is believed to occur once individuals are no longer able to or refuse to allocate additional resources to the task. More recent research (Unsworth & Robison, 2015) has also shown that individuals differentially allocate attention to items in WM as a function of the number of to-be-remembered items in a WM task. Specifically, during a delay period (after stimulus presentation and before recall) pupil dilation increased and reached an asymptote corresponding to the amount of items being maintained in one's WM. Results such as these led Kahneman (1973) to suggest that pupil dilation is a reliable and valid psychophysiological marker of attentional allocation. That is, TEPRs correspond to the intensive aspect of attention and provide an online indication of the amount of attentional effort devoted to a given item (i.e., the "intensity of attention"; Kahneman, 1973; Just & Carpenter, 1993).[1]

Using TEPRs, prior research has also linked pupillary responses at encoding to LTM performance (Ariel & Castel, 2014; Engle, 1975; Kafkas & Montaldi, 2011; Papesh, Goldinger, & Hout, 2012). For example, Ariel and Castel (2014) administered a value directed remembering task and found increased TEPRs for high value words relative to low value words. Notably, high value words were also associated with improved recall. Moreover, Papesh et al. (2012) demonstrated that the highest confident hits at test (i.e., items correctly recognized associated with the greatest confidence) were also associated with larger dilation during encoding. Thus, items that received the most attentional effort at encoding were more likely to be better remembered. While results such as these suggest the relation between TEPRs at encoding and ensuing LTM performance is *positive* in nature, it is important to acknowledge that the direction of this effect appears to be paradigm specific. Namely, using incidental learning conditions, Kafkas and Montaldi (2011) demonstrated the opposite pattern with pupil size when predicting recognition memory. Items that were subsequently remembered were associated with *decreased* TEPRs during encoding. Nonetheless, prior work adopting a similar procedure to ours (i.e., intentional learning conditions; Ariel & Castel, 2014; Goldinger, He, & Papesh, 2009; Papesh et al., 2012) collectively suggests that items associated with larger TEPRs at encoding receive more attentional effort, and these items are more likely to be better remembered.

The relation between pupil dilation at encoding and subsequent memory could be due, in part, to functioning of the locus coeruleus norepinephrine (LC-NE) neuromodulatory system, which is thought to be important for regulating attentional resources to maintain alertness and task engagement in a variety of situations (Aston-Jones & Cohen, 2005; Gilzenrat, Nieuwenhuis, Jepma, & Cohen, 2010; Sara, 2009). Prior research has shown an important link between pupil dilation and the LC-NE (Gilzenrat et al., 2010; Murphy, Robertson, Balsters, & O'Connell, 2011; Sterpenich et al., 2006) and has suggested that pupil dilation during encoding provides an indirect index of LC-NE functioning (Eldar, Cohen, & Niv, 2013). The LC has direct projections to the hippocampus (Samuels & Szabadi, 2008), and it has been suggested that the LC is critically important for memory formation, potentially due to attentional modulation of hippocampal neurons (Rowland & Kentros, 2008). Thus, the LC-NE system may be particularly important for modulating the intensity of attention to items during encoding, which results in stronger hippocampal representations that are then easier to retrieve at recall. Critically, the functioning of the LC-NE system may also be a source of individual differences in WMC and attention control (Unsworth & Robison, 2017a). People with low WMC and/or low attention control abilities may suffer from a dysregulation of LC activity, such that these individuals exhibit more fluctuations in LC activity than high ability individuals. Given the role of the LC-NE system in both memory formation and attention control, it seems increasingly plausible that individual differences in WMC could relate to differences in how much attention is allocated to items at encoding.

[1] We do not mean to suggest that phasic pupil dilation always indexes the intensity of attention. Pupillary responses also reflect changes in luminance (i.e., pupillary light reflex; Binda, Pereverzeva, & Murray, 2013), arousal (e.g., Janisse, 1977; Phaf & Wolters, 1993), and more (e.g., Bijleveld, Custers, & Aarts, 2009; Braem, Coenen, Bombeke, van Bochove, & Notebaert, 2015). We attempted to control for these influences in our procedure outlined in the method section but caution the reader to note that other processes may also be at play.