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The interactive influences of stress, modality of stimuli, and task difficulty on verbal versus visual working memory capacity

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A B S T R A C T

Recently, contradictory findings on the influence of stress on verbal and visual working memory (WM) have urged researchers to explore moderators of stress and the two types of WM. This study included perceived task difficulty as a moderator to investigate the interactive effects of stress, different types of stimuli, and perceived task difficulty on verbal and visual WM capacity. In the experimental study, 92 college students were randomly assigned to one of the following groups: high-stress verbal, low-stress verbal, high-stress visual, or low-stress visual. Saliva cortisol level was used as a proxy of stress. The results revealed that (1) stress enhanced visual WM capacity, but not verbal WM capacity; and (2) perceived task difficulty was an important moderator of WM capacity. Under stressful situations, perceived task difficulty may enhance attention, cognitive control, and processing efficiency through the modulation of cortisol responses, which further improves WM, especially visual WM. The findings suggest that interactions between stress, types of stimuli, and task difficulty should be taken into consideration concurrently to maximize the effects of learning.

1. Introduction

Working memory (WM) involves the "maintenance and/or manipulation of task-relevant information in the mind for brief periods of time to guide subsequent behavior" (Gazzaley & Nobre, 2012, p. 11). Such a capacity predicts achievement in a wide range of intellectual domains (Autin & Croizet, 2014). Theories of WM capacity will be more useful when we know what aspects of performance are governed by the limits and what aspects are influenced by other memory mechanisms (Cowan, Rouder, Blume, & Saults, 2012). Stress has been regarded as a potent modulator of brain function and cognition. However, the way stress influences WM is complex and controversial. Some studies have suggested that elevated stress is associated with poorer verbal WM (e.g., Bakvis, Spinhoven, Putman, Zitman, & Roelofs, 2010; Schwabe & Wolf, 2010) through the modulation of cortisol responses (Hoehn & Marieb, 2010). On the other hand, it has been reported that increased stress is associated with better visual WM (e.g., Lindström & Bohlin, 2011); stress may induce focused attention through the mechanism of stress hormones and, further, improve memory of relevant information (Joëls, Pu, Wiegert, Oitzl, & Krugers, 2006). Cortisol, also known as hydrocortisone, is a steroid hormone produced by the zona fasciculata of the adrenal gland; it is released in response to stress (Hoehn & Marieb, 2010). This study used cortisol concentration as an indicator of stress.

The contradictory findings regarding the influence of stress on WM have inspired studies investigating factors that may influence stress and memory as well as evaluating how stress and memory may interact under specific conditions (Bisaz, Conboy, & Sandi, 2009). Recent findings have revealed that interactions between memory and action processes are complex and dependent on such factors as the type of temporarily stored information (verbal vs. spatial) and the difficulty of tasks (Spiegel, Koester, & Schack, 2013). Past studies, however, seldom compare how stress (measured by cortisol) and the perceived difficulty of tasks may interact with stimuli modalities (verbal vs. visual) and, further, influence different types of WM capacity. This study aimed to investigate the effects of interactions between stress and perceived difficulty to task on verbal and visual WM capacity. In addition, because cortisol concentration gradually increases after manipulation (Yeh, Lai, Lin, Lin, & Sun, 2015), the goal of this study was also to understand the dynamic influence of stress on different types of WM as the WM tasks progress.

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1.1. Types of WM: visual versus verbal

WM is regarded to be an online cognitive process through which the learner processes new information and adjusts his or her behaviors to solve the encountered problem (Baddeley & Logie, 1999; Cowan, 1999). According to the multicomponent model of WM (Baddeley, 2000, 2003), WM is composed of four components: the central executive, which is an attentional control system of limited capacity; the visuospatial sketchpad, which functions as an interface between visual and spatial information; the phonological loop, which is responsible for storing and rehearsing auditory–verbal information; and an episodic buffer, which integrates information from both short-term stores and long-term memory and manipulates information of a visual or spatial nature. Both the visuospatial sketchpad and the phonological loop may include a passive perceptual store and an active rehearsal mechanism for refreshing the specific content of the buffer (Spiegel et al., 2013).

Neuroimaging studies have also suggested that verbal and spatial WM components are represented by different cortical networks (e.g., Gruber & von Cramon, 2003). Rothmayr et al. (2007) manipulated rehearsal strategies by instructing participants to maintain information either verbally or non-verbally; they found verbal rehearsal activated mainly left language-associated temporal and parietal areas, whereas non-verbal rehearsal mainly produced right dorsolateral prefrontal and medial prefrontal activation. In the same vein, Habeck, Rakitin, Steffener, and Stern (2012) found that the neural substrates of verbal and non-verbal rehearsal processes are similar but that their encoding processes seem to involve material-specific neural substrates. Therefore, WM involves different brain functions when it processed verbal and visual stimuli.

1.2. Influences of stress on different types of WM capacity

1.2.1. Stress and verbal WM

Previous studies have found that increased cortisol level is associated with inferiorretrieval of stored information from verbal memory (de Quervain, Roozendaal, Nitsch, McGaugh, & Hock, 2000; Kuhlmann, Piel, & Wolf, 2005; Sandi & Pinelo-Nava, 2007). Many studies have also suggested that acute stress is detrimental to verbal WM performances. For example, Smeets, Jelicic, and Merckelbach (2006) found that performance on recalling neutral words was impaired in the stress group and suggested that the memory effects of exposure to acute stress depend on the valence of the memory material. A recent meta-analysis also found that acute increases in cortisol level impaired WM (Shields, Bonner, & Moons, 2015). fMRI studies suggest such reduction in WM is linked to reduced activation of the prefrontal cortex (PFC) (Qin, Hermans, van Marle, Luo, & Fernández, 2009). Similarly, it has been reported that stress induced by public speaking impaired verbal WM in n-back tasks (Schoofs, Preuß, & Wolf, 2008) and digit-span tasks (Schoofs, Wolf, & Smeets, 2009); moreover, high levels of test anxiety increased difficulty in employing WM in test-related contexts (Shi, Gao, & Zhou, 2014).

In contrast, a few studies have suggested that stress, or increased cortisol facilitates verbal WM performance. Duncko, Johnson, Merikangas, and Grillon (2009) reported that exposure to the cold pressor stress test (CPS test) resulted in shorter reaction times in letter recognition tasks during trials with higher cognitive load. Oei, Tollenaar, Spinhoven, and Elzinga (2009) found that the hydro-cortisone group had enhanced WM performance with higher processing speed than the placebo group. More recently, Stauble, Thompson, and Morgan (2013) reported that cortisol secretion was positively associated with improvements in verbal WM; information must first be encoded before it is maintained, such improvements may reflect the advantageous nature of cortisol response at encoding.

1.2.2. Stress and visual WM

Comparatively, fewer studies focused on how stress or cortisol influence visual WM performance. A previous report suggested that cortisol negatively affected brain activities in brain regions involved in visual processing (Sudheimer, 2009) as well as retrieval of stored information from spatial memory (de Quervain et al., 2000). Similarly, it has been shown that high hydrocortisone level led to impairments in face recognition (Monk & Nelson, 2002). In contrast, it has been found that the level of hydrocortisone did not impact performance of visual memory tasks in the elderly (Porter, Barnett, Idey, McGuckin, & O'Brien, 2002). Furthermore, it had been demonstrated that increased stress induced by emotional stimuli in young people facilitated their visual WM performance in visual 2-back tasks (e.g., Lindström & Bohlin, 2011).

The positive effects of stress on visual WM can be explained by the theory of color-sharing effect and glutamatergic mechanisms. A recent eye movement study (Morey, Cong, Zheng, Price, & Morey, 2015) showed that color repetitions in a visual scene facilitated visual WM, suggesting that color-sharing effect facilitates perceptual organization of the display based on the presence of repetitions and strategic attention allocation when attention is available. Similar findings have been reported in related studies (Peterson & Berryhill, 2013; Quinlan & Cohen, 2012). It has been found that glutamatergic mechanisms are key mediators of the cognitive actions of acute stress (Conboy & Sandi, 2010). When stress is experienced in the context and around the time of an event that needs to be remembered, the hormones and transmitters released in response to the stress induce focused attention and improve memory of relevant information (Joëls et al., 2006). Therefore, stress hormones may induce focused attention and further improve visual WM performance.

1.3. Comparison of stress on verbal versus visual WM

It has been reported that the visuospatial sketchpad is associated with oculomotor control processes (Theeuwes, Olivers, & Chizk, 2005) and attention shifts (Postle, Awh, Jonides, Smith, & D'Esposito, 2004); moreover, verbal but not visual memory is disrupted by articulatory suppression between stimulus presentation and recall (Cocchini, Logie, Sala, MacPherson, & Baddeley, 2002). The aforementioned literature also favors the argument that stress is detrimental to verbal WM. On the contrary, other findings (Porter et al., 2002; Lindström & Bohlin, 2011) seem to be more supportive of the argument that stress has little influence on visual WM, or that stress can boost visual WM.

Young, Lopez, Murphy-Weinberg, Watson, and Akil (1998) suggested that two types of glucocorticoid receptors, the mineralocorticoid (MR; type I) and the glucocorticoid (type II) receptors, play a role in the regulation of the hypothalamic-pituitary-adrenal (HPA) axis and that MR activity is correlated with cortisol level; moreover, MR plays a clear role in HPA axis regulation during the peak of the circadian cycle. Thus, interference effects by stress on WM may depend on the type of stored information (verbal vs. spatial), attention, and timing of interferences. Accordingly, we proposed the following hypothesis:

Hypothesis 1. Individuals who receive different levels of stress treatment and different types of stimuli (verbal versus visual) would show differences in WM capacity as interventions progress. Specifically, as time goes by, the intervention effects of stress would get stronger, and stress would enhance visual WM capacity, but impair verbal WM capacity.

1.4. Interaction effects of stress and perceived task difficulty on WM

Task difficulty may be one factor contributing to the heterogeneous results regarding the influence of stress on WM (Renner & Beversdorf, 2010). Empirical studies seem to more consistently find that stress