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Research Report

Individual differences in working memory capacity are reflected in different ERP and EEG patterns to task difficulty

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ABSTRACT

This study examined whether there are neural markers of individual differences in working memory (WM) capacity and whether these differences are only manifest when performing a demanding WM task or at all levels of difficulty. Each subject's WM capacity was estimated using a modified digit span task prior to participation in an *N*-back task that varied difficulty from 1- to 4-back. While performing the *N*-back task, subjects wore scalp electrodes that allowed measurement of both event-related potentials (ERP) and event-related synchronization and desynchronization (ERS/ERD). Those subjects classified as low WM were more affected by the higher cognitive demands (many more errors in the 4-back task and generally slower responses) than those classified as high WM. These behavioral differences between the two groups were also apparent in the neural markers. Specifically, low WM subjects, when compared with high WM subjects, produced smaller P300 amplitudes and theta ERS, as well as greater alpha ERD at the most difficult level. Importantly, the observed differences in electrophysiological responses between the two groups were also observed at the lowest difficulty level, not just when the task challenged WM capacity. In addition, P300 amplitudes and alpha ERD responses were found to correlate with individual WM capacities independent of the task difficulty. These results suggest that there are qualitative neural differences among individuals with different WM capacities when approaching cognitive operations. Individuals with high WM capacities may make more efficient use of neural resources to keep their attention focused on the task-relevant information when performing cognitive tasks.

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1. Introduction

Working memory (WM) is a set of mechanisms involved in the temporary retrieval, maintenance, and manipulation of information for a wide range of cognitive operations (e.g., Baddeley, 1992, 2003). Individual differences in WM capacity have been shown to correlate with performance in a variety of tasks including learning, planning, comprehension and problem solving (Alloway, 2009; Conway, 1996; Engle, 1994) as well as with general fluid intelligence (Conway et al., 2002; Engle et al., 1999). Measures of WM capacity have also been shown to predict academic achievement better than measures of intelligence (Alloway and Alloway, 2010). Given the centrality of WM to human cognitive processing, it is important to better understand the nature of individual differences in WM capacity. Much of the earlier research employed paradigms such as the traditional digit span test (Dempster and Cooney, 1982), reading span task (Daneman and Carpenter, 1980) and operation span task (Conway, 1996; Turner and Engle, 1989) to explore individual differences in WM capacity and focused primarily on behavioral measures.

More recently, researchers have investigated WM effects within and between individuals using neuroimaging methods, relying extensively on the *N*-back paradigm both when employing functional magnetic resonance imaging (fMRI) (Braver et al., 1997; Jaeggi et al., 2007; Manelis and Reder, 2014; Owen et al., 2005) and event-related potentials (ERP) (Daffner et al., 2011; Gevins and Smith, 2000; McEvoy et al., 2001) studies. The *N*-back task requires that the subjects indicate whether the current stimulus is identical to the stimulus shown N presentations before. In a given block the value of N remains constant and blocks are more difficult the higher the value of N. For example, in the 1-back condition, subjects need only to hold the last item in WM, while the 2-back condition requires subjects to update two items to be held in WM as well as decide whether the item 2-back matches the current one. A reason for the popularity of this paradigm is that input and output aspects of the task do not vary with increased WM load. Specifically, the visual input (a sequential presentation of stimuli) and the nature of the response (one of two button presses) remain constant across values of N. Therefore, any differences in performance or neuroimaging measures across values of N can be attributed to differences in WM demands as opposed to differences in the visual display or nature of the response.

Parametric variations of difficulty in the *N*-back task have enabled researchers to investigate neural changes as a function of WM demands (Braver et al., 1997; Daffner et al., 2011; Jaeggi et al., 2007; McEvoy et al., 2001; Pesonen et al., 2007; Watter et al., 2001). However, there have been few studies that have examined whether load-dependent changes in neural responses vary across individuals that have been shown to have different WM capacities, with the exception of a recent ERP study by Daffner et al. (2011). In addition, previous neuroimaging studies using the *N*-back task have not gone beyond 3-back. There have been several behavioral studies that have gone as high as 4- and 5-back (Jaeggi et al., 2010; Juvina and Taatgen, 2007; Verhaeghen and Basak, 2005), but no neurophysiological recordings have examined performance at such a high load. The current study explored whether there were electrophysiological signatures of individual differences in WM capacity and whether these differences were only manifest when performing a highly demanding WM task or at all levels of difficulty. We recorded scalp electroencephalography (EEG) signals in order to measure both ERP and event-related synchronization/desynchronization (ERS/ERD) during performance of the *N*-back task that varied N from 1 to 4.

The ERS/ERD measure tracks task-related changes in the synchrony of underlying neural populations (Klimesch, 1999; Pfurtscheller and Lopes da Silva, 1999). While the high temporal resolution of ERP enables researchers to examine the time course of cognitive operations, the spectral EEG oscillation (represented by ERS/ERD) can provide information about the dynamics of functional network formation (Bastiaansen and Hagoort, 2003). There has been a number of studies that suggest both measures are correlated with attentional resource allocation, WM capacity and general cognitive abilities (Gevins and Smith, 2000; Grabner et al., 2004; McEvoy et al., 2001; Polich, 2007). In a review article, Polich (2007) demonstrated that the P300 component played a role in attentional resource allocation among concurrent operations. Gevins and Smith (2000) found that the P300 amplitudes are positively correlated with subjects' WM capacities and general cognitive abilities. They also examined brain oscillations and found this same positive correlation with individuals' WM capacities and cognitive abilities for the frontal theta (~3–7 Hz) ERS. Similarly, McEvoy et al. (2001) reported that theta ERS is greater in younger than older adults when performing the *N*-back task. Lee et al. (2005) proposed that theta oscillations might be responsible for regulating the activation of relevant information maintained in WM. Finally, while the theta ERS findings showed a positive correlation with larger WM capacity, Grabner et al. (2004) found that higher intelligence is associated with lower alpha (~8–12 Hz) ERD responses, reflecting more efficient brain functioning in those scoring high on intelligence tests.

To extend the findings from the above research, the current study examined the P300 ERP component and EEG oscillations in the low frequency band (<15 Hz, including both theta- and alpha-band oscillations), in particular focusing on how these measures differed for subjects with different WM capacities. The expectation is that subjects with higher WM, as compared with subjects classified as having lower WM capacity, will show better performance on behavioral measures, greater amplitudes for the P300, larger values of theta ERS and attenuated alpha ERD. This pattern of differences based on WM capacity is expected to be strongest at the more challenging level of the *N*-back task. Conceivably, neural signals at the high difficulty level may result from something other than individual differences in WM capacity, such as the subject's effort to seek various strategies (Jaeggi et al., 2007), or the low WM subject's inability to engage in such a difficult task. Therefore, we were interested in looking at whether differences in the electrophysiological response patterns would also be observed at the lowest difficulty level, which placed few demands on individuals' WM.

It is important to note that prior studies that have explored individual differences in WM tasks such as the *N*-back have classified subjects as high and low groups based on their performance in the task itself (e.g., Daffner et al., 2011; Jaeggi et al., 2007). To avoid this circularity problem, we used