



Comparing brain activations associated with working memory and fluid intelligence



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ABSTRACT

Working memory (WM) and fluid intelligence (*Gf*) are thought to be highly related, though psychometrically distinct cognitive constructs. Both are important in a wide range of cognitively demanding tasks, and predictive of success in educational, occupational, and social domains. From a cognitive perspective, WM and *Gf* may share a capacity constraint due to the shared demand for attentional resources. Neuroimaging investigations of these two cognitive constructs have suggested similar shared frontal and parietal areas of neural activation as well, though to our knowledge the two have not been investigated in the same population. Here, we examine group level functional activations for tasks of WM (dual n-back), *Gf* (Raven's Standard Progressive Matrices; RSPM), as well as a theoretically unrelated comparison task of visual word/pseudoword decoding (lexical decision task) in a large sample of healthy young adults ($N = 63$) aged 18–40. Consistent with previous research, results indicate large areas of fronto-parietal activation in response to increasing task demands for the n-back task (dorsolateral, ventrolateral, and rostral prefrontal cortex, premotor cortex, and posterior parietal cortex), which largely subsume similar but more circumscribed regions of activation for the RSPM and lexical decision tasks. These results are discussed in terms of a task-general central network which may underlie performance of WM, *Gf*, and word decoding tasks alike, and perhaps even goal-directed behaviour more generally.

1. Introduction

Working memory (WM), or the ability to maintain and manipulate task-relevant information over short periods of time, is a core cognitive ability in humans. Though WM shares much in common with the concept of ‘short term memory’ (i.e. cognitive architecture, capacity limitation, and functional neuroanatomy), it is the prospective use of information in the service of some goal or objective which distinguishes the two, and has largely motivated the use of the descriptor “working” (Eriksson, Vogel, Lansner, Bergström, & Nyberg, 2015; Linden, 2007). In this sense, WM is highly utilized in a wide variety of challenging tasks both in the laboratory and in everyday life, and is in fact highly related to general intellectual and reasoning abilities, or ‘fluid intelligence’. In the theory of Cattell (1963), fluid intelligence (denoted *Gf*) is the ability to adapt one's reasoning abilities to solve novel cognitive problems involving new information, and stands in contrast to ‘crystallized intelligence’ (denoted *Gc*) which draws heavily upon previously learned declarative information acquired from education or previous experience (Carpenter, Just, & Shell, 1990; Carroll, 1996; McGrew, 2009).

Fluid intelligence and WM are highly related psychological constructs, and are often described as being ‘almost’ isomorphic. Studies investigating the specific strength of the relationship between WM and *Gf* have noted moderate correlations with coefficients in the 0.3 to 0.9 range (see Burgess, Gray, Conway, & Braver, 2011; Colom, Rebollo, Palacios, Juan-Espinosa, & Kyllonen, 2004), and Martínez et al. (2011) reported that WM and *Gf* could not in fact be distinguished at the latent variable level. Thus, although WM is defined much more narrowly than *Gf*, research over the past several decades has identified it as a core psychological process responsible for driving much of the observable variation in human cognitive abilities. Indeed, making recently experienced stimuli subsequently accessible for brief periods is an essential component of our ability to act outside the bounds of the immediate moment, and to coordinate complex goal-directed behaviours (Baddeley, 1992; Repovš & Baddeley, 2006). Given the relative necessity and ubiquity of WM processes in day-to-day cognitive functioning, previous research has indicated a surprisingly small capacity of the WM system (Chuderski, 2013). Luck and Vogel (1997) estimated the average capacity to be approximately four items, with most individuals demonstrating a capacity between two and six items (Cowan,

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2001). Though small in absolute terms, these inter-individual differences in WM capacity appear to account for much of the variance observed in cognitively demanding tasks and situations, including reading comprehension, language abilities, mathematics, reasoning, problem solving, overall academic performance, and even ‘fluid intelligence’ more generally (Engle, Tuholski, Laughlin, & Conway, 1999; Eriksson et al., 2015).

A parallel approach to studying the psychometric association between WM and *Gf* is the investigation of the neural mechanisms associated with each, and their potential overlap in terms of observed patterns of activation in response to task-load (i.e. task difficulty/complexity). Shared components between tasks might represent capacity constraints in the domain of attention (see Halford, Cowan, & Andrews, 2007), or perhaps shared neural circuitry or cortical involvement between the two tasks (Buschkuhl, Hernandez-Garcia, Jaeggi, Bernard, & Jonides, 2014). Burgess et al. (2011) note that a better understanding of the core psychological and neural mechanisms involved in WM may help in developing better targets for intervention in training studies, and more accurate predictions about success or failure of such interventions. To this end, here we review literature examining typical activation patterns associated with two of the most commonly utilized tasks of WM and *Gf* in WM training studies: the dual n-back task, and Raven’s Standard Progressive Matrices (RSPM) respectively. In addition, we examine functional activation patterns associated with a comparison task that is theoretically unrelated to the domains of WM or *Gf*, in order to assess the specificity of observed activations for tasks in those domains. For this purpose, we chose a word/pseudoword decoding task (lexical decision task; LDT) that, contrary to *Gf*, draws heavily upon previously learned information (i.e. crystallized intelligence; Carpenter et al., 1990; Carroll, 1996; McGrew, 2009).

1.1. Neural mechanisms associated with the n-back task

The n-back task has been widely utilized in recent years to study WM both in the context of its neural bases (Owen, McMillan, Laird, & Bullmore, 2005; Rottschy et al., 2012), as well as how training with the task may serve to improve WM (see von Bastian & Oberauer, 2013 for a review; though see also Redick & Lindsey, 2013). The n-back task requires participants to monitor consecutive presentation of visual and/or auditory stimuli, and respond via button-press when the current stimuli matches that presented ‘*n*’ trials ago, where *n* typically ranges from one to three. As *n* is increased, task difficulty rises sharply and places larger demands on a number of key processes involved in WM, including monitoring, updating, and manipulation of remembered information (Owen et al., 2005). We chose to utilize a dual n-back task in this study to most closely match the training tasks implemented in trials of working memory training (see Jaeggi, Buschkuhl, Jonides, & Perrig, 2008). While the dual n-back task is considerably more difficult due to the multiple modalities of task demands (i.e. visual and auditory), at least one investigation has shown it to be similarly effective compared to a single n-back training task (i.e. visual only) in terms of training gain and transfer to untrained domains (Jaeggi et al., 2010). However, transfer of training gains from working memory tasks to untrained domains (e.g. fluid intelligence) remains an unresolved and controversial issue in the literature (see Clark, Lawlor-Savage, & Goghari, 2017; Simons et al., 2016).

Owen et al. (2005) conducted a meta-analysis of 24 imaging studies utilizing the n-back task in healthy adult populations. Their analysis revealed five consistent areas of activation across task variants, falling exclusively within the frontal and parietal lobes. First, the bilateral dorsolateral prefrontal cortex (DLPFC) is thought to be involved in organizational control of WM, reducing overall cognitive load in WM tasks by selecting appropriate organizational chunks. Interestingly, neuropsychological data appears to support this claim, as patients with damaged frontal lobes appear to be impaired on only some WM tasks

(Owen, Morris, Sahakian, Polkey, & Robbins, 1996). Second, the bilateral mid-ventrolateral prefrontal cortex was implicated in n-back activity and is thought to be associated with explicit encoding and retrieval of information, as well as attentional processes. Third, the bilateral rostral prefrontal cortex is thought to combine or integrate multiple cognitive processes, specifically when the operation of a single cognitive process is insufficient to meet the particular demands of a task. Fourth, bilateral medial premotor cortex was implicated and is thought to be involved in maintenance of visuospatial attention during working memory tasks. Finally, bilateral medial posterior parietal cortex (including precuneus and inferior parietal lobule) was implicated in n-back activations and has previously been associated with mediating shifts in attention, retaining task-related temporal information, and preparing for a given task.

Similarly, Rottschy et al. (2012) undertook a broader neuroimaging meta-analytic approach to model the neural correlates of working memory by investigating several WM-related tasks (e.g. the Sternberg Task, the delayed matching to sample task, and the delayed simple matching task) as well as the n-back. They identified what they called a “core” WM network which included areas predominantly in the frontal and parietal regions across both hemispheres: dorsolateral prefrontal cortex, lateral prefrontal cortex, anterior insula, premotor cortex, pre-supplementary motor area, intraparietal sulcus, superior parietal lobule, and anterior parietal area. Rottschy et al. (2012) note that their results are quite similar to the earlier findings of Owen et al. (2005), despite including a wider variety of WM tasks in their meta-analysis and perhaps divergent naming practices of given stereotaxic spaces or neural structures. The consistency of these results across task and stimuli types strongly implicate the above areas as comprising a “core” WM network, perhaps forming the neural underpinnings of all WM cognitive processes.

Interestingly however, this core WM network closely resembles patterns of activation observed in a wide variety of tasks beyond WM, particularly when task demands increase. For example a similar, though right-dominant, network is associated with selective attention (see Shulman, D’Avossa, Tansy, & Corbetta, 2002; Shulman et al., 2009), and largely similar networks studied outside the realm of intelligence have been termed the attention and working memory system (Cabeza & Nyberg, 2000), the cognitive control network (Cole & Schneider, 2007), and the task-positive network (Fox et al., 2005). The involvement of these same cortical areas in such a diversity of tasks suggest an even more fundamental role in cognition, and coordinating behaviour beyond WM. Indeed, the frontoparietal network implicated in WM processes has also been discussed in terms of an executive control network, a dorsal attention network (Yeo et al., 2011), a core executive (discussed in Rottschy et al., 2012), and a multiple demand network (Duncan, 2010) which may mediate goal-directed behaviour by rapidly organizing mental focus and separation of successive task steps. In this sense, the cortical areas involved in successful navigation of WM tasks, or what Duncan (2010) calls ‘multiple-demand cortex’, may be essential to keeping the mind focused on the task-relevant information at hand without regard to its cognitive modality (e.g. perceptual, mnemonic, motor-related), thus playing a central role in virtually all non-routine cognitive functions. Recall that this matches the traditional description of fluid intelligence quite well – i.e. the ability to adapt one’s reasoning abilities to solve novel cognitive problems involving new information (Carpenter et al., 1990; Carroll, 1996; McGrew, 2009).

1.2. Neural mechanisms associated with Raven’s progressive matrices

Raven’s Progressive Matrices (RPM; Raven, 1975; Raven, Raven, & Court, 1994) scores are highly correlated with a wide range of other tests of intelligence, and is regarded as the most general single test of non-verbal (i.e. fluid) intelligence (Alderton & Larson, 1990; Carpenter et al., 1990). The task presents participants with a series of

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