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Correlational structure of 'frontal' tests and intelligence tests indicates two components with asymmetrical neurostructural correlates in old age

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ABSTRACT

Both general fluid intelligence (g_f) and performance on some 'frontal tests' of cognition decline with age. Both types of ability are at least partially dependent on the integrity of the frontal lobes, which also deteriorate with age. Overlap between these two methods of assessing complex cognition in older age remains unclear. Such overlap could be investigated using inter-test correlations alone, as in previous studies, but this would be enhanced by ascertaining whether frontal test performance and g_f share neurobiological variance. To this end, we examined relationships between g_f and 6 frontal tests (Tower, Self-Ordered Pointing, Simon, Moral Dilemmas, Reversal Learning and Faux Pas tests) in 90 healthy males, aged ~73 years. We interpreted their correlational structure using principal component analysis, and in relation to MRI-derived regional frontal lobe volumes (relative to maximal healthy brain size). g_f correlated significantly and positively ($.24 \leq r \leq .53$) with the majority of frontal test scores. Some frontal test scores also exhibited shared variance after controlling for g_f. Principal component analysis of test scores identified units of g_f-common and g_f-independent variance. The former was associated with variance in the left dorsolateral (DL) and anterior cingulate (AC) regions, and the latter with variance in the right DL and AC regions. Thus, we identify two biologically-meaningful components of variance in complex cognitive performance in older age and suggest that age-related changes to DL and AC have the greatest cognitive impact.

1. Introduction

The brain's frontal lobes support a range of complex cognitive functions and comprise several densely interconnected, but structurally heterogeneous sub-regions. They are a major focus of interest in both neuropsychology and differential psychology. Here, we empirically bring together assessments from these two psychological approaches and relate them to regional volumes from the brain's frontal lobes in older age.

Tasks have been developed in the domain of experimental neuropsychology to elicit specific frontal brain activation patterns (from functional imaging) or be sensitive to behavioural profiles caused by focal frontal lesions (Stuss & Levine, 2002), which we shall call 'frontal' tests. The emerging picture from neuropsychology, based on lesion studies and functional neuroimaging, indicates modularity for frontal lobe structure–

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function mapping whereby distinct regions, whilst densely interconnected, each make discrete contributions to performance on tests of complex cognition. This has led to a broad segregation of function between dorsal and ventral frontal regions (MacPherson, Phillips, & Della Sala, 2002; Phillips & Della Sala, 1998; Sarazin et al., 1998; Steele & Lawrie, 2004; Stuss, Shallice, Alexander, & Picton, 1995).

Differential psychology aims to understand the nature and causes of individual differences in psychological traits and states, including cognitive abilities. Normal healthy individuals who perform well in one cognitive domain (such as processing speed, memory and reasoning) also tend to perform well in another (Carroll, 1993). Current neurobiological models of general intelligence (*g*; a central concept in differential psychology) indicate a central role for the functioning of dorsolateral and cingulate, but not ventral regions of the frontal lobes (Duncan, 2010; Jung & Haier, 2007). More recently however, the contribution of ventral regions to intelligence has also been suggested, using voxel-based morphometry (Colom et al., 2009; Narr et al., 2007) and lesion-based mapping (Barbey et al., 2012; Gläscher et al., 2009). Therefore, the relationships between the cognitive tests used in neuropsychology and differential psychology are of interest.

The frontal region of the brain is particularly susceptible to the effects of age. Its gross volume, cortex (volume and thickness) and white matter (volume and diffusion-based measures of integrity) show disproportionate age-related decreases compared to other parts of the brain (Burzynska et al., 2012; Driscoll et al., 2009; Fjell et al., 2009; Sullivan & Pfefferbaum, 2007). Increasing age is also accompanied by a decline in complex cognitive functioning indexed by some frontal tests (Kemp, Després, Sellal, & Dufour, 2012; Lamar & Resnick, 2004; MacPherson et al., 2002) and also general fluid intelligence (g_f; Deary et al., 2009; Salthouse, 2004). Despite the interest that differential psychologists and neuropsychologists share in the frontal lobes of the brain and how they age, there are few comparisons of scores from the tests produced by these two areas of psychology (Davis, Pierson, & Finch, 2011). It is important to capture all aspects of cognitive ageing if we are to understand its nature and determinants, but two key issues of validity levelled at frontal tests (Rabbitt, Lowe, & Shilling, 2001) have significantly hampered research on this issue in the cognitive ageing literature: vagueness of conceptual boundaries and uniqueness of theoretical construct.

1.1. Vagueness of conceptual boundaries

The cognitive processes that are disrupted by frontal lesions or are associated with increased Blood Oxygenation Level-Dependent (BOLD) response in functional magnetic resonance imaging (fMRI) studies have been ascribed a wide variety of names and models such that, “a common functional denominator would appear elusive” (Goldman-Rakic, 1993, p. 13 from Rabbitt et al., 2001). For example, Salthouse (2005) and Davis et al. (2011) both highlight the lack of consensus regarding definitions of ‘executive function’ and the diversity of methods used to assess it. Rabbitt (1997) observed that the common usage of ‘inhibition’ perpetuates misleading analogies between potentially unrelated functional processes.

1.2. Uniqueness of theoretical construct

Correlations between test scores for the same theoretical construct “should not be explainable in terms of individual differences in functional property other than the one they are supposed to measure” (Rabbitt et al., 2001, p. 11). Potential confounders of frontal tests may be that they all measure one single construct (e.g. g_f; Duncan, Burgess, & Emslie, 1995) and set of neural sub-systems, or that each test taps multiple latent constructs (also known as *task-impurity*; Miyake & Friedman, 2012; Rabbitt, 1997; Salthouse, 2005) and distinct neural sub-systems. Moreover, strong lesion-symptom double dissociations in the literature remain the exception rather than the rule, and the dense reciprocal connectivity amongst frontal areas has clearly made it difficult to elucidate the specific functional contributions that sub-regions might make. Whereas it is plausible that frontal regions make unique processing contributions to task performance (e.g. Zald, 2007), the current literature might suggest that, at worst, an anatomically pure test of frontal sub-regional function is unattainable (Nyhus & Barceló, 2009), and at best, such a task has not yet been developed (e.g. Manes et al., 2002).

When addressing both criticisms, we propose that taking a neurobiological perspective considerably alters our expectations and interpretation of cognitive test covariances. For example, the following strongly relate to measures of intelligence: putative tests of shifting and working memory (Lehto, Juuarvi, Kooistra, & Pulkkinen, 2003), subtests from the Delis–Kaplan Executive Function System (D-KEFS; Floyd, Bergeron, Hamilton, & Parra, 2010), CANTAB factors of planning and set-shifting (Robbins et al., 1998), Stroop and Tower tests (Crawford, Bryan, Luszcz, Obonsawin, & Stewart, 2000; Salthouse, 2005), a factor of updating (Friedman et al., 2006), and a unitary executive function comprised of inhibition, working memory and shifting tests (Brydges, Reid, Fox, & Anderson, 2012). Salthouse also reported that the age effects that were present for the Stroop and Tower tests (Salthouse, 2005) and a variant of the Trail Making test (Salthouse, 2011) were entirely explained by the relationship between age and either reasoning or perceptual speed. The distinct nomenclature (e.g. ‘intelligence’, ‘shifting’, ‘working memory’) sets up an expectation of several unique theoretical constructs, in opposition to the obvious interpretation of these data (i.e. each appear to broadly measure the same construct). Yet, by considering these prior data in light of the proposed neural correlates of g_f and frontal tests, reported correlations between some neuropsychological tests and general fluid intelligence scores are a realistic expectation because both are consistently linked with common frontal sub-regions (whereas, for other frontal tests and g_f, the converse is true). Dorsolateral prefrontal cortex (DLPFC) and dorsal anterior cingulate cortex (dACC) functioning are implicated in g_f (Duncan, 2010; Jung & Haier, 2007) and performance on the Tower test (see Methods), Trail Making test (e.g. Yochim, Baldo, Nelson, & Delis, 2007; Zakzanis, Mraz, & Graham, 2005) and stimulus–response conflict tasks such as the Stroop (e.g. Peterson et al., 2002) and Simon tasks (see Methods). By contrast, tests such as the Faux Pas test thought to tap other (non-g_f-implicated) ventromedial frontal regions such as the orbitofrontal cortex (OFC) may not be expected to show such strong associations with intelligence amongst normal, young, healthy populations.