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Cognitive specialization for verbal vs. spatial ability in men and women: Neural and behavioral correlates

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ABSTRACT

An important dimension of individual differences, independent of general cognitive ability (GCA), is specialization for verbal or spatial ability. In this study we investigated neuroanatomic, network, and personality features associated with verbal vs. spatial ability. Healthy young adults (N = 244) were evaluated with (1) a cognitive battery yielding measures of verbal and spatial ability independent of GCA, (2) structural MRI scans providing measures of surface area, cortical thickness, and DTI scans allowing calculation of diverse network metrics, and (3) Big-5 personality measures. Sex differences were found for cognitive, personality, anatomic, and network measures. In men only, cortical surface was significantly, differentially related to the cognitive variables, predicting spatial but not verbal ability. Similarly, in men only, neuroticism and quirkiness (the overall deviation from the mean across scales) were significantly, differentially related to the two cognitive variables. Different graph metrics predicted spatial ability in men (overall connectivity) and women (clustering). Verbal-spatial specialization was related to sex, cortical surface area, network organization, personality, and vocational interests. Most of the identified correlates of this cognitive specialization were found only in men, and mostly for spatial ability. Taken together, these results identify a suite of neurobehavioral features whose covariance is partially sex-specific.

1. Introduction

In recent years a great deal has been learned about the neurobiological underpinnings of general intelligence, from neurophysiology (Neubauer & Fink, 2009) to neuroanatomy (Vuoksimaa et al., 2015) and network science (van den Heuvel et al., 2009). Much less is known, however, about the neurobiology of cognitive specialization. Independent of general cognitive ability (GCA), what brain features confer relatively better verbal or spatial ability? Such cognitive specialization potentially has a great impact on many life issues, perhaps most prominently on our choices in educational and occupational realms (Lubinski, 2010). Further, clinical correlates of specialization have long been identified through analysis of verbal vs. spatial discrepancies emerging from the many Wechsler intelligence scales (Bishop & Butterworth, 1980).

Our general goal is to investigate verbal vs. spatial cognitive specialization with many of the analytic tools that have proven useful in establishing the nomological net of GCA: assessment of gross morphological correlates, graph theory analysis of brain networks, examination of possible sex differences in neurobehavioral relationships, and exploration of non-cognitive correlates.

Morphological studies of cognitive variation typically examine cortical volume, and less often, its constituents of cortical thickness and surface area. Importantly, different genetic factors are related to thickness and surface area (Panizzon et al., 2009; Winkler et al., 2010). Some studies report greater heritability of mean cortical thickness than surface area (Ge et al., 2015), but others do not (e.g., Winkler et al., 2010). Two recent studies investigated the importance of variations of cortical thickness for verbal vs. spatial specialization. Karama and colleagues studied verbal and spatial reasoning in a large sample (N = 207) of children and adolescents, and found that after controlling for GCA neither skill was related to cortical thickness (Karama et al., 2011). Margolis et al. studied a wide age range (5–57) of healthy individuals (N = 83) who had been given one of several versions of the Wechsler scales,

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yielding Verbal IQ (VIQ) and Performance IQ (PIQ) scores (Margolis et al., 2013). To remove variance associated with GCA, they analyzed VIQ-regressed on PIQ (pure verbal) and PIQ regressed on VIQ (pure spatial). Greater cortical thickness across anterior and posterior brain regions was associated with better spatial ability, but *worse* verbal ability. This intriguing result raises the possibility of a developmental trade-off: perhaps one cannot simultaneously optimize the neural substrate of each skill.

Behavior genetic studies of cognition have revealed an interesting distinction between GCA and specific cognitive skills. GCA shows substantial heritability, but more specific skills show very little heritability after GCA variance has been removed (Deary, 2012). Thus, non-genetic factors may be especially important for cognitive specialization. These results are consistent with the proposition that phenotypic correlations among diverse cognitive skills generally reflect mutual genetic covariation with GCA (Plomin et al., 2013).

Sex differences have long been observed in verbal vs. spatial specialization, with females sometimes showing slightly better verbal skills and males slightly better spatial skills (Halpern, 2012). These sex differences suggest a causal role for sex hormones and environmental factors as determinants of specialization. Sex differences are also observed in non-cognitive realms, including personality (Del Giudice et al., 2012) and psychopathology (Martel, 2013; Rutter et al., 2003), but relationships with cognitive specialization are poorly understood. More generally, modest correlations have been reported between Openness, a Big 5 personality trait, and GCA. To our knowledge, correlates of pure measures of spatial and verbal skills with personality have not been reported.

Graph theory quantifies important features of brain networks as derived from both structural and functional imaging data (Rubinov & Sporns, 2010). Several studies have reported sex differences in graph metrics (e.g., Ingalhalikar et al., 2014) and have revealed some general principles of how graph metrics relate to GCA: better connectivity, more efficiency, and shorter characteristic path length are often found to predict higher GCA (e.g., Cole et al., 2012; Li et al., 2009). Presumably, the neural computations underlying verbal vs. spatial reasoning differ, and the graph metrics relevant for each may potentially differ.

In this study we report a comprehensive analysis of verbal vs. spatial cognitive specialization in a large sample of healthy young adults. Following the methods of Karama et al. (2011) and Margolis et al. (2013)we focused on verbal ability, after controlling for spatial ability, and spatial ability, after controlling for verbal ability. We hypothesize that spatial ability, but not verbal ability, will be positively correlated with surface area. We also hypothesize that, like GCA, greater specific verbal or spatial skill will be associated with Openness. In an attempt to derive a personality variable that may be akin to "cognitive specialization" we explored the correlates of a novel personality trait we term "quirkiness" or the general tendency to deviate from typicality across traits. Next we explore global graph metrics of white matter network organization from diffusion-weighted structural MRI imaging and related these to our ability measures. We also predict that cognitive specialization has a "real world" impact on the choice of college majors.

2. Methods

2.1. Participants

This study was conducted according to the principles expressed in the Declaration of Helsinki, and was approved by the Institutional Review Board of the University of New Mexico. Participants were recruited by postings in departments and classrooms around the University of New Mexico. Twelve (4.7%) were excluded due to the low quality of their neuroimaging data (i.e. motion or image artifacts) or missing cognitive testing data, resulting in 244 human participants in the final sample. Participants were young adults (125 males, mean age = 21.84 (SD = 3.55) and 117 females, mean age = 21.71 (SD = 3.44) and all had an interest in science, technology, engineering, and math (STEM) fields, broadly defined using the 2012 revised list of USA degree programs (http://www.ice.gov/sites/default/files/documents/Document/2014/stem-list.pdf). We distinguished two types participants: "social science" majors (e.g., psychology, sociology) vs. "hard science" majors (physics, engineering).

2.2. Procedures

2.2.1. Cognitive assessment

Several cognitive tasks tapped verbal and spatial skills. Participants were also administered a variety of tests tapping creativity that will not discussed here (see Ryman et al., 2014; Jung et al., 2015). No prior studies with this data set have explored either spatial or verbal ability. The spatial tasks were the Block Design and Matrix Reasoning subtests from the Wechsler Abbreviated Intelligence Scale II (WASI-II; Wechsler, 2011), the Paper Folding test from the Johnson O'Conner Research Foundation (JCORF) battery (Condon & Schroder, 2003; Haier et al., 2009), and the Mental Rotation Tests (MRT; Peters et al., 1995). The verbal tests were the Similarities subtest of the WASI-II and the Vocabulary subtest from the JOCRF. Reliability of the WASI-II subtests is excellent (Wechsler, 2011) and the JOCRF Vocabulary test (r = 0.96) and Paper Folding test (r = 0.82) also show good reliability. The WASI-II and JOCRF test were administered according to standard procedures; participants completed as many MRT items as possible in 4 min. All test scores were converted to z-scores; the mean of the four spatial test z-scores yielded a measure of spatial ability and the mean of the two verbal tests yielded a measure of verbal ability. Following the methods of Margolis et al. (2013) we then created "pure" spatial and verbal measures through regression procedures. For each, we simply regressed one on the other and saved the residuals. These more pure variables were used in all subsequent analyses of each cognitive skill. We also computed a verbal minus spatial difference score.

2.2.2. Personality assessment

The Big Five Aspects Scale (BFAS) was used to assess personality (DeYoung et al., 2005). In addition to examination of the big-5, we were interested in deriving a measure of personality that might capture an effect similar to cognitive specialization, that is, deviation from population-typical, balanced profiles. A measure of personality "quirkiness" was derived by (1) calculating the absolute values of the difference between each facet score and the sample mean, and (2) summing these absolute values. This variable captures multivariate deviation from the typical personality.

2.2.3. Neuroimaging acquisition

MRI data were acquired on a 3-Tesla Siemens Triotim MRI scanner located at the Mind Research Network in Albuquerque, New Mexico using a 32-channel head coil. The multiecho MPRAGE protocol was followed to obtain the T1 image: [TE 1.64/3.5/5.36/7.22/9.08 ms; TR 2530 ms; voxel size 1x1x1mm; 192 slices; Field of View = 256 mm; acquisition time 6.03]. For the diffusion weighted imaging (DWI) data echo planar imaging was acquired: [TE 110 ms; TR 3600 ms; voxel size $2.2 \times 2.2 \times 2.2$ mm^3; 66 slices; Field of View = 229 mm; 150 diffusion directions with b = 1000–3000 s/mm^2, and 6 measurements with b = 0, acquisition time 9:36].

2.2.4. Morphometric analysis

The MPRAGE T1 images were used for anatomical references and for the selection of the nodes of the brain network. Methods for cortical reconstruction and volumetric segmentation were performed with the FreeSurfer image analysis suite (http://surfer.nmr.mgh.harvard.edu/). Thickness, volume, and surface area measurements were obtained by reconstructing representations of the gray matter/white matter boundary and the pial surface. The results of the automatic segmentations were quality controlled and any errors were manually corrected. The