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Individual differences in cognitive performance and brain structure in typically developing children

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ABSTRACT

Individual differences in cognitive patterning is informative in understanding one's cognitive strengths and weaknesses. However, little is known about the difference in brain structures relating to individual differences in cognitive patterning. In this study, we classified typically developing children ($n = 277$; age range, 5–16 years) into subtypes with k-means cluster analysis along with factor index scores using the Wechsler Intelligence Scale for Children (Third Edition). We then applied voxel-based morphometry to investigate whether significant gray-matter-volume differences existed among subtypes of cognitive patterns. Depending on the level of performance and cognitive patterning, we obtained six subtypes. One subtype that generally scored below average showed larger volume in the right middle temporal gyrus than the other five. On the other hand, two subtypes that achieved average levels of performance showed reverse-patterned factor index scores (one scored higher in Verbal Comprehension and Freedom from Distractibility, and the other scored lower in these two factor index scores) and had smaller volume in the right middle temporal gyrus than the other subtypes. From these results, we concluded that cognitive discrepancy was also obvious in typically developing children and that differences in cognitive patterning are represented in brain structure.

1. Introduction

The intelligence quotient (IQ) has played a significant role in clinical psychology. The Wechsler Intelligence Scale for Children (WISC) is one of the most widely used measures of psychometric intelligence in children. It is used in various contexts such as clinical, academic, and school settings. This instrument has excellent psychometric properties, especially in terms of its standardization and the reliability of the full-scale IQ (FSIQ), two composed scores that are verbal IQ (VIQ), performance IQ (PIQ), and four factor index scores (VC: verbal comprehension, PO: perceptual organization, FD: freedom from distractibility, and PS: processing speed) (Kaufman, 1993). Some practitioners have reported the importance of the profile analysis of factor index scores or sub-test scores with respect to patterning (Donders, 1996). The discrepancy pattern of cognitive functions measured by WISC is useful for better understanding the cognitive strengths and weaknesses of children.

In psychology, previous studies have categorized individual cognitive patterns using factor index scores in typically developing children (Donders, 1996; Glutting et al., 1994), as well as in clinically referred children or children with neurodevelopmental disorders, such as autism, traumatic brain injury, or attention deficit and hyperactivity disorder (ADHD) (Allen et al., 1991; Donders and Warschausky, 1997; Hale et al., 2013; Mayes and Calhoun, 2004, 2006; Siegel et al., 1996; Waxman and Casey,

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2006). The number of subtypes has been varied from 3 to 8 according to the characteristics of participants or versions of the WISC. Glutting et al. (1994), who investigated the pattern of factor index scores combined with the Wechsler Individual Achievement Test of composite scores, revealed six subtypes within 824 typically developing children and found that the six subtypes were characterized by general performance level (above-average, average, and below-average) and the discrepancy of sub-scores. Similarly, Donders (1996) clarified five subtypes within 2200 children from WISC-III standardization samples. Three out of the five subtypes were featured by the performance levels (above-average, average, and below-average overall performance levels), and the remaining two were featured by performance patterns. The results of Glutting et al. (1994) and Donders (1996) suggest that cognitive patterns can be classified into subtypes on the basis of general performance level and the discrepancy of factor index scores, even in typically developing children.

The relationship between brain structure and IQ has been reported by several previous studies. Regarding the neural basis of cognitive functions, several studies have found the correlation between composite scores of the WISCs or Wechsler Adult Intelligence Scales (WAISs) and brain size and between volume or thickness of cortical areas and white matter integrity in normal populations (Burgaleta et al., 2014; Haier et al., 2004; Jung and Haier, 2007; Lee et al., 2006; Sowell et al., 2001; Sowell et al., 2004). Willerman et al. (1991) examined the relationship between brain size and intelligence, demonstrating positive correlation between IQ scores and brain size. Wilke et al. (2003) investigated 146 children (age range: 5–18 years), revealing a tendency for the correlation between FSIQ and global gray matter volume and regional gray matter volume (rGMV) in the anterior cingulate cortex. Frangou et al. (2004) examined 40 young participants (mean age of 14.26 years), revealing a significant positive correlation between FSIQ and rGMV in the cerebellum, orbitofrontal cortex, thalamus, cingulate, and precuneus and a significant negative correlation in the caudate nucleus. Haier et al. (2004) found correlations among rGMV within frontal (Brodmann areas (BA) 10, 46, 9), temporal (BA 21, 37, 42), parietal (BA 43, 3), and occipital (BA 19) lobes in adolescents and adults. From the results of previous findings, rGMV and the frontal, temporal, and parietal regions are positively correlated with FSIQ. Furthermore, the previous studies on cortical thickness revealed that brain regions that positively correlated with FSIQ include areas in the frontal (inferior, anterior, or superior), temporal (anterior, superior), and parietal cortices (Burgaleta et al., 2014; Choi et al., 2008; Karama et al., 2013; Margolis et al., 2013; Narr et al., 2007).

Previous brain structure and function studies mainly focused on FSIQ as cognitive function. However, little is known about the neural basis of the discrepancy of cognitive functions among individuals. Considering the taxonomy of cognitive patterning in the normal population, brain structure was considered to differ among subtypes. Moreover, the number of participants in previous imaging studies was relatively small. Therefore, in this study, we examined the relationship between brain structure and cognitive subtypes of typically developing children obtained from a large sample. Identifying the relationship between brain structure and cognitive pattern would help to explore the biological underpinnings of intelligence and the specific cognitive patterns associated with neurodevelopmental disorders.

We hypothesized that the subtypes of cognitive pattern emerged depending on the performance levels (above-average, average, and below-average) and performance patterns. Brain structures previously associated with IQ, including the prefrontal, temporal, and parietal cortex, were significantly related to certain cognitive profile subtypes.

2. Methods

2.1. Participants

We collected brain magnetic resonance (MR) images from 298 healthy Japanese children (152 boys and 146 girls; age range: 5.6–18.4 years). The details related to their initial recruitment have been reported in our previous study (Taki et al., 2010). Using an advertisement issued to local schools, we recruited only right-handed children with no history of malignant tumors or head traumas involving the loss of consciousness. Using the Edinburgh Handedness Inventory, we confirmed that all participants were right handed (Oldfield, 1971). As per the Declaration of Helsinki (1991), after explaining the purpose and procedures of the study, written informed consent was obtained from each participant and his/her parent prior to MR scanning. Approval for this study was obtained from the Institutional Review Board of Tohoku University.

All participants performed the age-appropriate version of Wechsler intelligence scales (Japanese version of WAIS, Third Edition, or WISC, Third Edition). Then, we selected participants whose intelligence was measured using the WISC-III. This yielded 289 children with an age range of 5–16 years. Because of issues with the quality of imaging data or lack of effective data for psychological variables, the analyses that were performed with 277 participants (138 boys and 139 girls) are as follows.

2.2. Assessments of psychological variables

On the same day of scanning, intelligence was measured using the WISC-III, administered by trained examiners. Using the raw scores of participants, we calculated three IQ scores (FSIQ, VIQ, and PIQ) and four factor indexes (VC, PO, FD, and PS) for each participant.

Socio-economic status was also measured using the three questions as follows. One was an enquiry relating to family annual income, as reported in our previous study (Taki et al., 2010). Annual income data were collected using discrete variables: 1, annual income <US$ 20,000 (the currency exchange rate was set at US$ 1 = 100 yen); 2, annual income US$ 20,000–40,000; 3, annual income US$ 40,000–60,000; 4, annual income US$ 60,000–80,000; 5, annual income US$ 80,000–100,000; 6, annual income US$ 100,000–120,000; 7, annual income ≥US$ 120,000. The values 1–7 were used in subsequent regression analyses. The other two questions related to the highest educational qualification of both parents. There were eight options: 1, elementary school graduate or below; 2, junior high school graduate; 3, high school graduate; 4, graduate of a short-term course completed after high school (such as junior college); 5, university graduate; 6, Masters degree; and 7, Doctorate, and each choice was converted into the number of years taken to complete the qualification in a normal manner in the Japanese education system (1, 6 years; 2, 9 years; 3, 12 years; 4, 14 years; 5, 16 years; 6, 18 years; 7, 21 years). The average of converted values for each parent was used in the analyses. This protocol followed the standard approach used by the Japanese government for evaluating socio-economic status.

2.3. Behavioral data analysis

Behavioral data was analyzed using SPSS version 20 (IBM, Japan). In the unsupervised classification approach, we applied K-means cluster analysis to classify the participants along with the pattern of their factor index scores. Following the procedure applied by Thaler et al. (2013), we increased the number of cluster solutions from three until reaching the point where a minimum of one cluster that contained less than 10% of the entire sample appeared. Thereafter, a supervised classification approach, discriminant function analysis, was performed with factor index scores as