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Healthy children show gender differences in correlations between nonverbal cognitive ability and brain activation during visual perception

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HIGHLIGHTS

- We examined the brain activation of 121 healthy children using fMRI.
- Nonverbal ability was positively correlated with the right TPJ activation in DMS.
- Children show gender differences in brain activation of rTPJ during visual perception.
- The correlation between nonverbal ability and rTPJ activation was more robust in boys.

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ABSTRACT

Humans perceive textual and nontextual information in visual perception, and both depend on language. In childhood education, students exhibit diverse perceptual abilities, such that some students process textual information better and some process nontextual information better. These predispositions involve many factors, including cognitive ability and learning preference. However, the relationship between verbal and nonverbal cognitive abilities and brain activation during visual perception has not yet been examined in children. We used functional magnetic resonance imaging to examine the relationship between nonverbal and verbal cognitive abilities and brain activation during nontextual visual perception in large numbers of children. A significant positive correlation was found between nonverbal cognitive abilities and brain activation in the right temporoparietal junction, which is thought to be related to attention reorienting. This significant positive correlation existed only in boys. These findings suggested that male brain activation differed from female brain activation, and that this depended on individual cognitive processes, even if there was no gender difference in behavioral performance.

Abbreviations: DMS, delayed match-to-sample; EPI, echo planar images; fMRI, functional magnetic resonance imaging; FSIQ, full-scale IQ; FWE, family-wise error; POI, perceptual organization index; PSI, processing speed index; SPM 5, statistical parametric mapping 5; TPJ, temporoparietal junction; VCI, verbal comprehension index; VFC, ventral frontal cortex; WISC, Wechsler intelligence scale for children; WMI, working memory index.

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1. Introduction

Visual perception is necessary to acquire information about the external environment so that we can perform daily life activities. Perceptual organization involves structures that process the disparate visual information in sensory memory into coherent units that we experience as environmental objects. Visual attention is the mechanism by which some visual information in a scene is selected. Recent research has demonstrated important relationships between attention and perceptual organization and that they constrain each other [13]. For example, visual attention affects the perception of letters [25], and visual attention predicts reading acquisition [7]. The visual perception of textual information depends on language, culture, age, knowledge, and other factors. In particular, nontextual visual perception is also affected by language [29].

During children's education, students have to obtain much of their information through the visual perception of textual and nontextual materials. Moreover, some students are better at processing textual information, and some students are better at processing nontextual information. These predispositions involve a number of factors, including cognitive ability, learning preference, and cognitive style [16,17]. Hence, individual differences in verbal and visual cognitive abilities are thought to affect the visual perception of the contents of teaching materials.

However, to the best of our knowledge, the relationship between individual verbal or nonverbal cognitive abilities and neural activity during visual perception in children has not yet been revealed. Only a few studies have investigated this relationship and have only used fMRI in adults [14,18,19]. Thus, we performed this study to help contribute to a better understanding of visual information processing in children and to reveal the neural basis of correlations between individual differences in visual perception and verbal and nonverbal cognitive abilities.

In this study, we focused on the relationship between the individual differences in nonverbal and verbal cognitive abilities and brain activity during visual perception with attention. We used a visual delayed match-to-sample (DMS) task as our nontextual information-processing task. DMS tasks have been used to measure numerous cognitive abilities, including selective attention, working memory, working memory retrieval, memory decay, goal maintenance, and active maintenance [6,22]. Many studies in humans and nonhuman animals have shown that the DMS task appraises primal visual perception. We measured cognitive abilities from an intelligence test battery score that is commonly used to assess general cognitive abilities in children.

The purpose of this study was to identify the neural basis of the relationship between nonverbal cognitive ability and brain activation during nontextual visual information processing tasks in healthy children. In order to achieve these goals, we conducted an fMRI experiment in children performing a DMS task, and an intelligence test. We examined the correlations between brain activity and visual, verbal, and other general cognitive abilities. We hypothesized that brain activation during the DMS task might correlate with visual perceptual ability, which is thought to be a measurement of nonverbal cognitive abilities in the brain regions of the attention system.

2. Materials and methods

2.1. Participants

Right-handed, healthy Japanese children ($n = 172$) participated in this fMRI experiment as part of our larger-scale brain development research project in healthy children [26,27]. Their age range was 6–18 years (mean age, 12.1 years; standard deviation [SD], 3.0 years). Subjects who had any history of malignant tumors, head trauma with a loss of consciousness lasting more than five minutes, developmental disorders, epilepsy, psychiatric diseases, or claustrophobia were excluded through a preliminary telephone interview, a mail-in health questionnaire, and an oral interview by medical doctor. Handedness was evaluated with the Edinburgh Handedness Inventory [21]. All of the participants were recruited from kindergartens, elementary schools, junior high schools, and high schools in Miyagi Prefecture in Japan. Written informed consent was obtained from each participant and his or her parent, and the study met all of the criteria for approval by the Institutional Review Board of Tohoku University Graduate School of Medicine. The imaging analysis of this study included data from 121 participants (60 boys and 61 girls; age range, 6–16 years; mean age, 11.3 years; standard deviation [SD], 2.4 years), in order to exclude large head movements and poor performance for analysis. All participants also completed the Japanese version of the Wechsler intelligence scale for children (WISC)–III [31–34].

2.2. Cognitive ability

The WISC–III can measure individual differences in nonverbal and verbal cognitive abilities.

We calculated the full-scale IQ (FSIQ) and four sub-indices, the verbal comprehension index (VCI), perceptual organization index (POI), processing speed index (PSI), and working memory index (WMI), from participants' WISC scores. The POI is a measure of nonverbal and in-the-moment reasoning and is considered a reflection of various aspects of visual functioning [8]. The VCI is a measure of general verbal skills, such as verbal fluency, the ability to understand and use verbal reasoning, and verbal knowledge. We also used the FSIQ, WMI, and PSI as measurements of general cognitive ability, working memory, and processing speed, respectively.

2.3. Task

We performed an fMRI experiment with a DMS task and a block-design paradigm. The DMS task has three stages: identification of the sample, retention during delay, and the matching of the sample and target in visual perception [9]. All of the stages recruit attentional orienting to objects in the task procedure. In the DMS task used in this study, the subjects were instructed to remember a visually presented sample figure for 1 s. After the sample figure disappeared, the subject was instructed to select a figure matching the sample figure from two subsequently presented target figures. The presentation period of all of the figures was set to 1 s to prevent the visual information of the figures from being converted into verbal information during the selection portion of the task (Fig. 1). Accuracy and reaction times were recorded. To help understand the procedure before scanning, all of the subjects were instructed and trained on the task with a personal computer.

2.4. Image acquisition

All MRI data acquisition was conducted with a 3 T Philips Intera Achieva scanner. Forty-two gradient-echo echo planar images (EPI; echo time = 30 ms, flip angle = 90°, slice thickness = 3 mm, slice gap = 0 mm, field of view = 192 mm, matrix size = 64 × 64, voxel size = 3 mm × 3 mm × 3 mm) covering the entire cerebrum were acquired at a repetition time of 2500 ms. Seventy-eight EPI volumes were acquired for each participant.

2.5. Preprocessing

We performed a preprocessing series with statistical parametric mapping 5 (SPM5; Wellcome Department of Cognitive Neurology,