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Research Report

The neural basis of syllogistic reasoning: An event-related potential study

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ABSTRACT

The spatiotemporal analysis of brain activation during syllogistic reasoning, and the execution of 1 baseline task (BST) were performed in 14 healthy adult participants using high-density event-related brain potentials (ERPs). The following results were obtained: First, the valid syllogistic reasoning task (VSR) elicited a greater positive ERP deflection than the invalid syllogistic reasoning task (ISR) and BST between 300 and 400 ms after the onset of the minor premise. Dipole source analysis of the difference waves (VSR-BST and VSR-ISR) indicated that the positive components were localized in the vicinity of the occipito-temporal cortex, possibly related to visual premise processing. Second, VSR and ISR demonstrated greater negativity than BST developed at 600–700 ms. Dipole source analysis of difference waves (VSR-BST and ISR-BST) indicated that the negative components were mainly localized near the medial frontal cortex/the anterior cingulate cortex, possibly related to the manipulation and integration of premise information. Third, both VSR and ISR elicited a more positive ERP deflection than BST between 2500 and 3000 ms. Voltage maps of the difference waves (VSR-BST and VSR-ISR) demonstrated strong activity in the right frontal scalp regions. Results indicate that the reasoning tasks may require more mental effort to spatial processing of working memory.

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1. Introduction

Syllogistic reasoning is derived from pairs of categorical premises. For example, given that all A are B (major premise), and all B are C (minor premise), this reasoning is applied to conclude whether all A are C is a valid conclusion. It is an important form of reasoning that involves the interpretation of implicit information under the given premises. Some syllogistic premises are easy to interpret and others are very difficult; therefore, typically only a few participants can deduce the correct conclusion. At present, there is a disagreement about the origin of this divergence in interpretation. For example, those who propose theories based on formal rules claim that people solve reasoning problems by means of a set of inference rules. In other words, they believe that reasoning is mainly a linguistic process (Braine and O'Brien, 1998; Rips, 1994). This explanation is directly challenged by the theory of mental model. This theory is based on the assumption that people draw inferences by means of visuospatial mental models on the basis of the "state of the affairs" described in the premises and not on the hypothesis that there is a mental natural deduction system (Johnson-Laird and Byrne, 2002;

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Johnson-Laird, 2001; Ruff et al., 2003). Since these hypothesized operations mainly depend on visuospatial processes, in order to harmonize the conflict between rule-based theory and mental theory, Evans (2002, 2003) and Goel (2003) suggested that there are 2 sets of different reasoning process systems with a relevant neurobiological foundation. This is known as the theory of dual-process reasoning. In this theory, System 1 is a rapid, parallel, and automatic process mainly located in the frontal-temporal pathway, and System 2 is a slow, serial process involving working memory together with the parieto-occipital pathway.

Neuroimaging techniques have provided new insights that transcend these debates (Goel et al., 1997, 1998, Goel et al., 2000, Goel and Dolan, 2001; Goel and Dolan, 2003; Knauff et al., 2002; Ruff et al., 2003; Noveck et al., 2004); however, a consensus has not been achieved on the cognitive mechanism of syllogistic reasoning. For example, Goel et al. (1997, 1998) observed that the areas activated during different deductive reasoning processes (including categorical syllogisms and three-term spatial relational items) were confined to the left hemisphere and were similar to each other. This included the left inferior frontal gyrus, the left middle temporal gyrus, and a portion of the left cingulate gyrus. There was no significant activation of the right hemisphere or the parietal cortex. Recently, both the studies of Goel and Dolan (2003) and Noveck et al. (2004) led to 2 kinds of novel findings. One finding was that the neural effect was based on the content of thought. The parietal-frontal pathway was activated when participants reasoned with arbitrary materials, whereas the temporal-frontal system, which is linked to language areas, was activated when participants reasoned with syllogisms using realistic statements (which correspond to one's beliefs). The second finding from their work was regarding the right hemisphere, which appeared to be recruited during the resolution of conflict. On the basis of this finding, it was inferred that reasoning is a dual system (Goel, 2003). However, Ruff et al. (2003) investigated the neuronal processes underlying reasoning using functional magnetic resonance imaging (fMRI), and their results supported the notion that relational reasoning was based on visuospatial mental models. In another study, Knauff et al. (2002) confirmed that the activation of the occipito-parietal pathway might be involved in spatial perception and spatial working memory and the prefrontal cortical areas (the anterior cingulate gyrus) might be related to higher cognitive functions. In short, they suggested that reasoners envisage and inspect spatially organized mental models to solve deductive problems (Knauff et al., 2002; Ruff et al., 2003).

In a recent study, Fangmeier et al. (2006) reported that the reasoning process follows 3 temporally separable phases: (1) the premise-processing phase, (2) the premise-integration phase, and (3) the validation phase. They investigated the neurocognitive processes underlying deductive reasoning with fMRI and found distinct patterns of cortical activity during these 3 phases, with initial temporooccipital activation shifting to the prefrontal and then the parietal cortex during the reasoning process. However, the time course of cortical activation cannot be studied with precision by using positron emission tomography (PET) and fMRI. Many of these studies examined brain activation during the entire reasoning process in a blocked fashion, and thus could not distinguish reasoning-related processes during different stages of problem processing. Thus, it is unclear whether reasoning is associated with subprocesses distinct from sentence processing and how these subprocesses may be differentially involved in different stages of syllogistic reasoning. Event-related potentials (ERPs) may provide a means to evaluate timing of cognitive processes prior to a response. In the ERP technique, recordings are made of the electrical activity of the brain that is time-locked to the presentation of an external stimulus. Therefore, ERP data would allow for more precise statements about the time course of activation of the different cognitive processing of reasoning.

The purpose of the present study was to investigate the spatiotemporal patterns of brain activity during the performance of syllogistic reasoning tasks [a valid syllogistic reasoning (VSR) task and an invalid syllogistic reasoning (ISR) task] and one baseline task (BST), using high-density (64 channels) event-related potential (ERP) recording and dipole source analysis (BESA software). Firstly, we wanted to identify the ERP components that are involved in inference processing by comparing between the ERPs during the syllogistic reasoning and the baseline task and whether there is any difference among these components. Based on previous studies (e.g., Donchin and Coles, 1988; Mecklinger and Pfeifer, 1996; Fangmeier et al., 2006), we hypothesized that the ERP components (e.g., P300 and late slow waves) may be related to the different cognitive processes of syllogistic reasoning (e.g., premise-processing phase, premise-integration phase, and validation phase). In addition, neural mechanisms might be different for the reasoning task and the baseline task. This assumption was based on findings of previous fMRI studies (e.g., Goel et al., 2000; Goel, 2003; Noveck et al., 2004; Fangmeier et al., 2006) that showed that the neural networks (e.g., with initial temporooccipital activation shifting to the prefrontal and then the parietal cortex during the reasoning process) involved in human syllogistic reasoning may be different from those involved in baseline tasks (e.g., semantic judgment). The method of high-density (64 channel) ERP recording and voltage mappings used in this study can provide critical temporal information for analyzing the functional neuroanatomy of cognitive processes involved in syllogistic reasoning; this data may help to validate the results of previous studies and facilitate the thorough investigation of brain mechanisms involved in syllogistic reasoning. To the best of our knowledge, this is the first ERP study investigating the electrophysiological correlates of syllogistic reasoning.

2. Results

2.1. *Behavioral data*

In VSR, ISR and BST conditions, the average numbers (percentage) of correct conclusion judgments were 48 ± 17 ($60.0 \pm 21.2\%$), 54 ± 11 ($67.5 \pm 13.7\%$), 54 ± 12 ($67.5 \pm 15.0\%$), respectively; and the mean response times (RTs) were 789 ± 93 ms, 744 ± 137 ms and 740 ± 69 ms, respectively. Repeated-measures ANOVA showed that there was no significant effect of task type for the mean accuracy and the mean RTs.

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