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Neural bases of falsification in conditional proposition testing: Evidence from an fMRI study

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ABSTRACT

The ability of testing the validity of a conditional statement is important in our everyday life. However, the brain mechanisms underlying this process, especially falsification process which is important in daily life, but especially crucial to scientific reasoning and research is not as yet completely clear. Therefore, in the present study, we used event-related functional magnetic resonance imaging (fMRI) to examine the neural bases of the falsification process in testing the validity of a conditional statement as used in Wason's (1966) selection task. Our fMRI results showed that: (1) compared with the baseline condition, both Falsification (by using Modus Ponens, and Modus Tollens) and Non-Falsification conditions (affirming the consequent, and denying the antecedent) activated the left frontal areas (BA44/45, or BA6), and basal ganglia, the areas previously found in the rule-guided conditional reasoning operations; the parietal area (BA40, BA7) for recruiting cognitive resources to represent and maintain the different evidential information in working memory. (2) The left middle frontal gyrus (BA9) and cerebellum were shown to be activated in the contrast of Falsification condition versus Non-Falsification condition and in the contrast of MT versus Non-Falsification condition. These results indicated that the left middle frontal gyrus (BA9) might be the key brain region involved in the falsification process of conditional statement for which abstracting and integrating logical relationships, and inhibiting the distraction of the irrelevant information were the essential processes. Moreover, the cerebellum was found to be responsible for constructing an internal working model. In addition, our brain imaging results might support the dual-process theory of reasoning.

1. Introduction

A conditional statement is also known as an *If…Then…* statement. For example, *If you press the brake pedal* (p), *then the car stops* (q). The first clause of the statement (represented conventionally by the letter p) specifies a condition, and the second clause (represented by the letter q) a consequent. There are four conditional reasoning modes: *Modus Ponens* (*MP*), *Modus Tollens* (*MT*), *denying the antecedent* (*DA*), and *affirming the consequent* (*AC*). Each mode of reasoning is illustrated in the following:

MP: If p, then q
 p
 Therefore, q
MT: If p, then q
 Not q
 Therefore, not p
DA: If p, then q
 Not p
 Therefore, not q
AC: If p, then q
 q
 Therefore, p.

MP and MT are valid inferences, but DA and AC are invalid inferences. In the Wason's (1966) selection task, participants were presented with 4 two-sided cards each with a letter or number on each side (e.g., "E", "7", "K", "4") (these 4 characters are equivalent to p, *not* q, *not* p, *and* q). Participants' task was to select the minimum number of cards to turn over to test the validity of the statement "*If* the card has a vowel on one side, *then* it has an even number on the other side"). Since MP and MT are the valid forms of reasoning, "E" and "7" should be the correct choices (Liberman and Klar, 1996). The ability of conducting accurate conditional reasoning is essential not only in the scientific research, but also in our daily life. Therefore,

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it is important to understand the neural bases of the cognitive processes underlying the conditional proposition testing such as that in Wason's selection task.

It is important to note that a conditional proposition can never be proven true although it can be proven false. In other words, verification of a conditional statement is not a possibility but falsification is possible. For example, the conditional statement "If a card has an odd number on one side, then it has a lowercase letter on the other side" cannot be possibly verified because this conditional statement defined a rule about a set of numbers (e.g., the category of odd numbers) and a set of letters (e.g., the category of lowercase letters).We cannot verify the statement "A bird can fly" by demonstrating "A robin can fly" is true. However, we can prove "An ostrich can fly" false falsifies the statement "A bird can fly". We provided a detailed explanation of this logic to our participants before the experiment. Only the choices of "P" and "not Q" can possibly falsify the conditional statement, and therefore conclusively test the proposition (Hanson et al., 2001). That is to say, proposition testing is a complex cognitive process, including logical reasoning, affirming the verifiable example and falsification.

As for now, there were three major reasoning theories (the mental logic theory, the mental model theory and the dual-process theory) disputed by researchers in reasoning field (proposition testing). Specifically, the mental logic theory claimed that people solved reasoning problems based on the formal rules and believed that reasoning was mainly a linguistic process (see e.g., Braine and O'Brien, 1998; Rips, 1994; Qiu, 2009). If this theory was right, the process of reasoning should result in the left frontal and temporal lobe regions (language areas; Goel, 2003; Qiu, 2007) activation. However, the mental model theory assumed that people draw inferences mainly depend on visuospatial processes (Johnson et al., 2002; Ruff et al., 2003). That is to say, the reasoning should activate right hemisphere and parietal which were related to visuospatial process (Goel, 2003; Qiu, 2007). In fact, some previous studies had pointed out that the mental logic theory indicated the brain mechanism of reasoning process was the pathway from the temporal lobe and frontal lobe, whereas, the mental model theory was the pathway from parietal lobe and frontal lobe contributed to the reasoning process (Johnson-Laird, 2010; Byrne and Johnson-Laird, 2009; Reverberi et al., 2010). In addition, the dual-process theory thought that there are two distinct cognitive systems underlying reasoning. System 1 or the Heuristic System is an evolutionarily old, rapid, parallel, automatic process which is mainly in the frontal–temporal pathway; and System 2 or the Analytic System is a slow, rule-based, sequential in nature and serial process together with working memory in the parietal–occipital pathway (Evans, 2003; Goel, 2003; Goel et al., 2000; Prado and Noveck, 2007; Qiu, 2007).

Research using brain-imaging techniques had provided considerable data on the neural correlates of conditional reasoning and tests these theories. For example, Noveck et al. (2004) applied fMRI to explore the neural basis of conditional reasoning with arbitrary materials. They found that relative to the baseline task, the left superior parietal lobule, the left temporal lobe and the language areas were activated by Modus Ponens and the left superior parietal lobe, the left frontal and prefrontal gyrus were activated by Modus Tollens forms of reasoning. Recently, Prado et al. (2010) also found that the left inferior frontal gyrus was involved in integrating the premises of conditional reasoning. Reverberi et al. (2007) further showed that the left inferior frontal gyrus and the left inferior parietal gyrus were important in conditional reasoning (see also Reverberi et al., 2010). Moreover, they thought that the frontoparietal network represented the neural basis of the generation of conclusions in elementary propositional deductive problems (Reverberi et al., 2007). In addition, many neuroimaging studies of reasoning indicated that the left prefrontal gyrus played an important role during the reasoning (Canessa et al., 2005; Fangmeier et al., 2006; Goel and Dolan, 2001, 2003, 2004; Goel et al., 1997; Heckers et al., 2004; Knauff et al., 2003, 2000, 2002; Noveck et al., 2004; Prado and Noveck, 2007). Moreover, Goel et al. (2000) suggested that content based reasoning recruited a left temporal system whereas reasoning with abstract formal problems was associated with activation of a parietal system, and then the two systems share common components in bilateral basal ganglia nuclei, right cerebellum, and left prefrontal cortex (two distinct networks were involved; Goel et al., 2000; Evans, 2003). Similarly, Goel et al. (2004) compared patients with focal frontal lobe damage and normal controls on Wason's selection task using content problems drawing on social knowledge. Their results showed that normal controls displayed the expected improvement in the social knowledge conditions, but frontal lobe patients failed to perform this task (Goel et al., 2004). Moreover, they found that the frontal lobe activation in the task was asymmetric, and reinforced the viewpoint that the frontal lobe was necessary for reasoning about social situations (Goel et al., 2004). Reis et al. (2007) also investigated the neural basis of social-exchange reasoning, using Wason's selection task paradigm, and found that "higher emotional intelligence predicted hemodynamic responses during social reasoning in the left frontal polar and left anterior temporal regions". According to a patient with impaired social reasoning, Stone et al. (2002) found the frontal cortex and anterior temporal lobe were engaged in reasoning about social exchange. Elliott and Dolan (1998) presented participants with hypothesis testing tasks which required the participants to identify a rule that would determine which of these two checkerboards was correct, and found that hypothesis testing activated the cerebellum, the left anterior cingulate, the right precuneus, the right thalamus, and the left inferior frontal gyrus. Therefore, based on these findings, we thought that the frontal cortex and parietal lobe might be both recruited for proposition testing. Specifically, there might be some brain regions such as the left inferior frontal gyrus and the left inferior parietal gyrus that were expected to be involved in the falsification process. Thus, it might be important and necessary for us to explore the brain mechanism of falsification process and test the dual-process theory.

In sum, conditional reasoning is not only an ability that is inevitable for everyday life but also a complex and important cognitive process. Up to now, lots of studies only focused on the brain regions associated with reasoning. In particular, few studies have reported the specific brain regions involved in conditional proposition testing, especially the neural bases of the falsification mode in testing the conditional statement. In the scientific research, every problem or issue must have the property of falsification, but people were impacted by the bias of verification or other bias. It is important to gain a clear idea of the neural mechanism of the falsification. Therefore, in the present study, we used functional magnetic resonance imaging (fMRI) to make a close examination of the neural bases of testing the conditional proposition by falsification (the only correct way of testing it). Moreover, we wanted to explore the brain mechanism of falsification process directly and test these different views of logical reasoning theories profoundly. In our study, we used an item with abstract content to exclude the impacts of emotion and life experiences on the brain activities we were observing. In a trial of our experiment, participants were presented with a conditional statement along with a probe symbol (e.g., the letter "E" or the numeral "9") equivalent to a particular card in Wason's task. Their task was to determine what role the probe symbol can play in testing the conditional statement. Based on previous findings (see e.g., Noveck et al., 2004; Reverberi et al., 2007, 2010; Goel et al., 2004; Elliott and Dolan, 1998), we thought that there would be some special neural mechanisms associated with falsification in conditional proposition testing, and we predicted that the left prefrontal gyrus would be activated when making a falsification response to an abstract conditional statement. In addition, we also predicted that an area of the cerebellum would be likely to be responsible for constructing an integrated internal model on the basis of different probe symbols.