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# Neural Mechanisms for Dual-Process Reasoning: Evidence from the Belief-Bias Effect

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## 1. Introduction

Recent neuroimaging studies have increasingly focused on the neural mechanisms of human deductive reasoning (see Goel, 2006 for recent review). Deductive reasoning is the cognitive process of drawing valid conclusions from a given set of premises. Although it should be performed independently of prior knowledge and intuitive beliefs, actual human reasoning often relies on them. Sometimes such beliefs provide valid solutions to problems, though they can also bias our judgment. This tendency toward bias in human reasoning has been experimentally studied through the demonstration of belief-bias effect in syllogistic reasoning (De Neys, 2006a, 2006b; Tsujii et al., 2006).

Belief-bias effect refers to the tendency of subjects to be more likely to accept the conclusion to a syllogism if they find it believable than if they disbelieve it, irrespective of its actual logical validity (De Neys, 2006a, 2006b; Tsujii et al., 2006). The experiment of belief-bias effect includes two types of syllogisms: one in congruent trials, in which the logical conclusion is consistent with beliefs about the world (valid-believable and invalid-unbelievable), the other in incongruent trials, in which the logical conclusion is inconsistent with beliefs (valid-unbelievable and invalid-believable). A typical material design was presented in Fig.1. Belief-bias thus facilitates logical responses in congruent trials, while it opposes logically correct responses in incongruent trials (De Neys et al., 2008; De Neys & van Gelder, 2009b; Goel & Dolan, 2003; Tsujii & Watanabe, 2009, 2010; Tsujii et al., 2010a, 2010b, 2011).

One explanation for the belief-bias effect is offered by the dual-process theory of reasoning, which proposes the existence of two different human reasoning systems (Evans, 2003, 2008; De Neys, 2006a, 2006b). The first system, often called the heuristic system, tends to solve problems by relying on prior knowledge and belief. The second system, often called the analytic system, engages in reasoning according to logical standards. The schematic representation of the dual-process theory was presented in Fig. 2. The heuristic default system is assumed to operate rapidly and automatically, whereas operations of the analytic system are believed to be slow and heavily demanding of computational resources (De Neys, 2006a, 2006b; Tsujii & Watanabe, 2009, 2010). The aim of this chapter was to summarize the recent neuroimaging findings which supported the dual-process account of deductive reasoning, focusing on studies of the belief-bias effect.

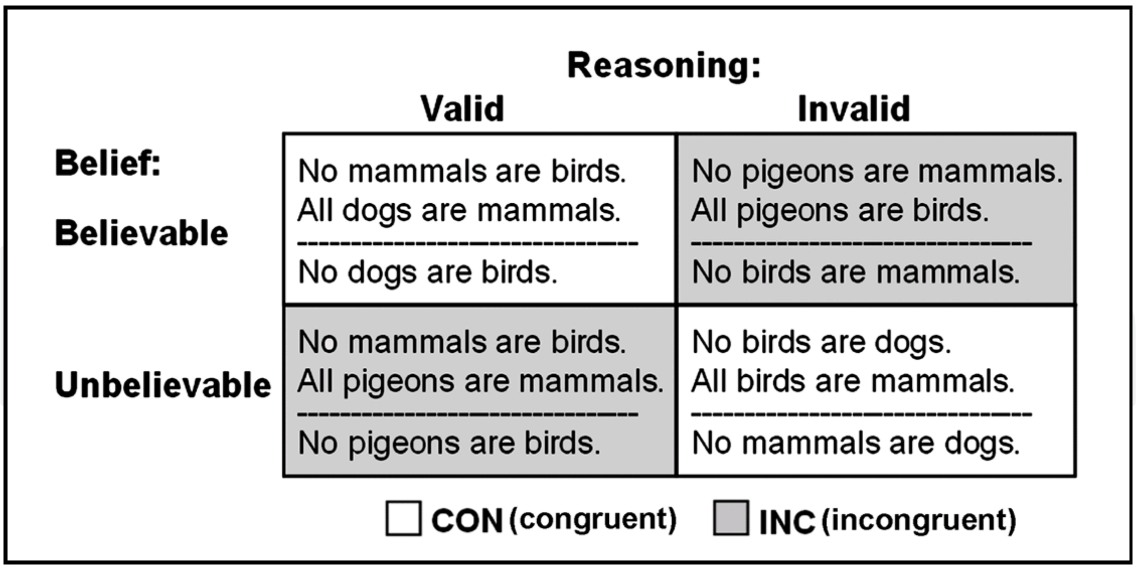


Fig. 1. Material design of the belief-bias effect

Several neuroimaging studies using functional magnetic resonance imaging (fMRI) have examined the neural mechanisms of belief-bias reasoning (Goel, 2007). These studies reported that the belief-bias effect was associated with right inferior frontal cortex (IFC) activity (De Neys et al., 2008; Goel & Dolan, 2003). Right IFC activity was enhanced when subjects could respond correctly to incongruent reasoning trials. The authors of these studies claimed that the right IFC plays a role in inhibiting the default heuristic system for successful logical reasoning (De Neys et al., 2008; Goel & Dolan, 2003).

In general, the right IFC activity is known to play a central role in inhibitory function (Aron et al., 2004, 2007). For example, response inhibition has been found to be associated with the right IFC activity in several tasks, including the go/no-go task (Chikazoe et al., 2007, 2009; Chiu et al., 2008; Rubia et al., 2001; Tsujii et al., 2011b) and the stop-signal task (Aron and Poldrack, 2006; Hampshire et al., 2010; Rubia et al., 2001, 2003). Furthermore, when subjects changed from one task to another (task-set switching), the right IFC activity was also enhanced (Cools et al., 2002; Smith et al., 2004, 2006; Xue et al., 2008). In addition, other studies have suggested that the right IFC deficit may underlie the impaired response inhibition in patients with attention-deficit hyperactivity disorder (Durston et al., 2006, 2011; Rubia et al., 2005, 2010). These observations are consistent with the claims of dual-process theory that the right IFC plays a functional role in inhibiting the default heuristic system to enable analytic logical reasoning system activity (De Neys et al., 2008; Goel, 2007; Goel & Dolan, 2003). In the present paper, we further presented recent studies in our laboratory which examined the attention-demanding and time-consuming properties of the right IFC activity in belief-bias reasoning (Tsujii & Watanabe, 2009, 2010).

While most of the neuroimaging studies of deductive reasoning have used fMRI (Goel et al., 2000; Goel and Dolan, 2001, 2003; Knauff et al., 2002, 2003; Monti et al., 2007, 2009; Reverbeli et al., 2007, 2009, 2010), our laboratory utilized two relatively new imaging technique: one is functional near-infrared spectroscopy (fNIRS) and the other is repetitive transcranial magnetic stimulation (rTMS). fNIRS is the imaging technique for investigating cortical hemodynamic responses by measuring changes in the attenuation of near-infrared light passing through tissue. Since oxygenated hemoglobin (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb) have different absorption spectra in the infrared range, changes in concentrations of oxy- and deoxy-Hb can be calculated by detecting infrared light at two different wavelengths on the skull (approximately 787 and 827 nm). In general, enhanced oxy-Hb and reduced deoxy-Hb are associated with regional cortical activation. NIRS is non-invasive, robust against body movement and has been validated as a suitable technique for investigating neural mechanisms in psychological experiments (Tsujii et al., 2007, 2009a, 2009b, 2010b, 2010c, 2011b).

Although fMRI and fNIRS studies have provided interesting findings of the neural mechanisms of deductive reasoning, they can only examine correlations between cortical areas and a type of behaviour. The second aim of the present study was to demonstrate recent findings of rTMS studies in our laboratory which elucidated the roles of the inferior frontal cortex (IFC) and the superior parietal lobule (SPL) in human deductive reasoning (Tsujii et al., 2010a, 2011a). Especially, we adopted an off-line rTMS method in which low-frequency rTMS is delivered to a specific brain area over several minutes to disrupt normal functioning of this area transiently after stimulation (Devlin et al., 2003; Hamidi et al., 2008, 2009; Hilgetag et al., 2001; Miller et al., 2008; Robertson et al., 2003). We investigated the effect of off-line rTMS of IFC and SPL on subsequent reasoning performance of congruent and incongruent trials. The rTMS approach can establish the causal relationships between brain and behaviour more directly compared with fMRI and fNIRS.

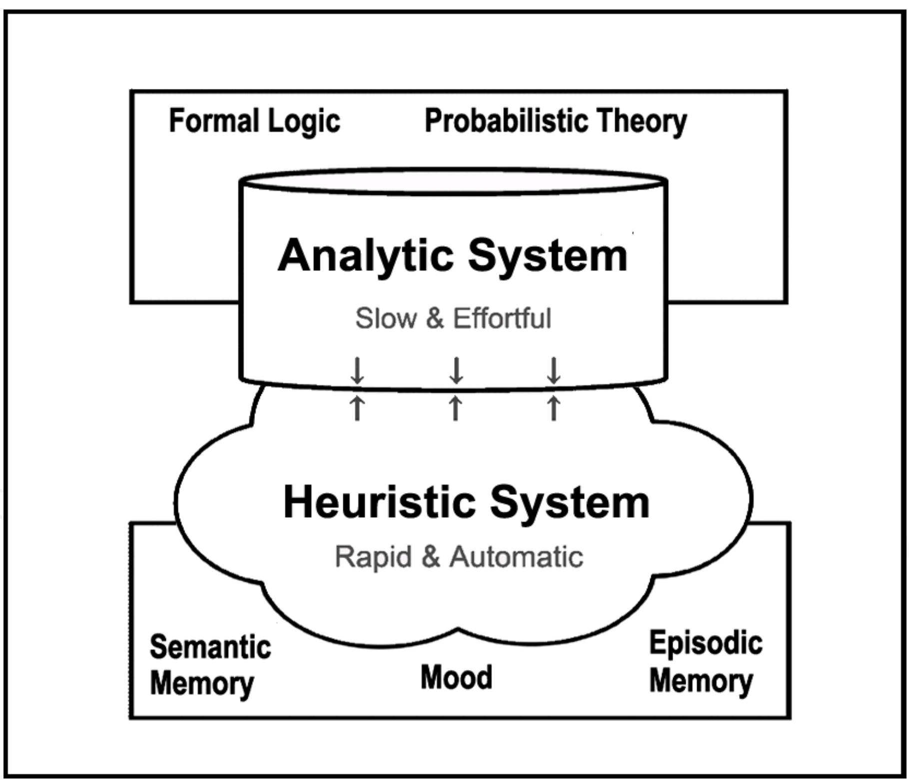


Fig. 2. Schematic illustration of the dual-process theory

## 2. fNIRS studies: Dual-task and time-pressure effects on reasoning

The dual-process theory claimed that the heuristic default system is assumed to operate rapidly and automatically, whereas operations of the analytic system are believed to be slow and heavily demanding of computational resources. Although these claims were supported by behavioural findings (De Neys, 2006a, 2006b), the neural correlates of dual-task and time-pressure effect on belief-bias reasoning was unknown. Thus, a series of fNIRS studies in our laboratory examined the attention-demanding and time-consuming properties of the analytic reasoning system and IFC activity using fNIRS (Tsujii & Watanabe, 2009, 2010). In addition, we examined the aging effect on hemispheric asymmetry in IFC activity using fNIRS (Tsujii et al., 2010b).

### 2.1 Dual-task effect on belief-bias reasoning

Tsujii & Watanabe (2009) examined the relationship between dual-task effect and IFC activity during belief-bias reasoning by fNIRS. Previous behavioural studies demonstrated that subjects with poor working memory capacity exhibited larger belief-bias effect than those with rich working memory capacity (De Neys, 2006a, 2006b; Stanovich & West, 2000). More directly, De Neys (2006a) found that attention-demanding concurrent tasks impaired incongruent but not congruent reasoning trials. These findings suggest that the analytic system is attention-demanding, and that when attention is divided by a concurrent task, individuals tend to rely on the automatic heuristic system, resulting in belief-bias responses. Although these behavioural findings are important, the neural correlates of dual-task reasoning are still unclear.

Tsujii & Watanabe (2009) therefore examined the neural correlates of the dual-task effect on IFC activity in belief-bias reasoning using fNIRS approach. Subjects were asked to perform a syllogistic reasoning task, involving congruent and incongruent trials, while responding to attention-demanding secondary tasks, in which a white square stimulus appeared at one of the four corners of a black screen throughout the experiment (Fig. 3). In the low-load condition, subjects were required to respond whenever the stimulus was in a predetermined location (e.g. upper-left position). In the high-load condition, subjects were asked to respond when the current stimulus was in the same location as the stimulus two trials previously (2-back).

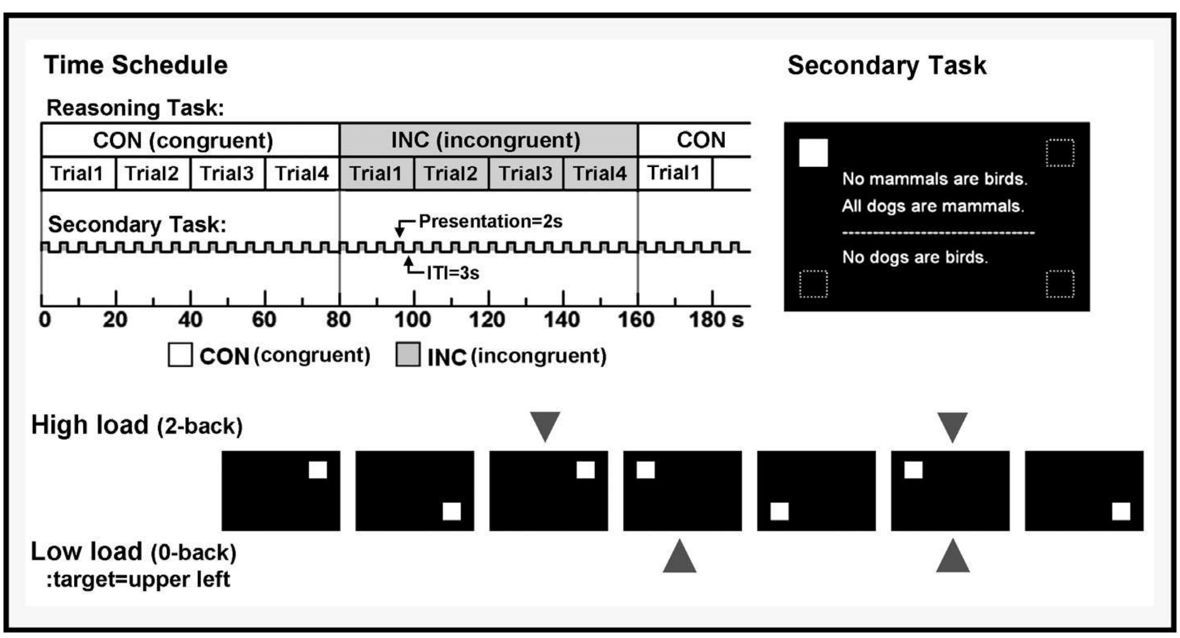


Fig. 3. Time schedule and schematic drawings of the secondary task.

Behavioural analysis showed that the high-load secondary task impaired only incongruent reasoning performance. NIRS analysis found that the high-load secondary task decreased right IFC activity during incongruent trials. Correlation analysis showed that subjects with enhanced right IFC activity could perform better in the incongruent reasoning trials, though subjects for whom right IFC activity was impaired by the secondary task could not maintain better reasoning performance. These findings suggest that the right IFC may be responsible for the dual-task effect in conflicting reasoning processes. When secondary tasks impair right IFC activity, subjects may rely on the automatic heuristic system, which results in belief-bias responses. Tsujii & Watanabe (2009) therefore offer the first demonstration of neural correlates of dual-task effect on IFC activity in belief-bias reasoning.

### 2.2 Belief-bias reasoning under time-pressure

Tsujii & Watanabe (2010) addressed the difference in speed between the heuristic and analytic reasoning systems. The dual-process theory of reasoning explained the belief-bias effect by proposing a belief-based fast heuristic system and a logic-based slow analytic system. Although the claims were supported by behavioural findings that the belief-bias effect was enhanced when subjects were not given sufficient time for reasoning (De Neys, 2006b; Evans & Curtis-Holmes, 2005), the neural correlates were still unknown. Tsujii & Watanabe (2010), thus, examined the neural correlates of the time-pressure effect on the IFC activity in belief-bias reasoning using fNIRS. Subjects were asked to perform a syllogistic reasoning task, involving congruent and incongruent trials, both in long-span (20 s) and short-span conditions (10 s).

Behavioural analysis found that only incongruent reasoning performance was impaired by the time-pressure of short-span trials. NIRS analysis found that the time-pressure decreased right IFC activity during incongruent trials. Correlation analysis showed that subjects with enhanced right IFC activity could perform better in incongruent trials, while subjects for whom the right IFC activity was impaired by the time-pressure could not maintain better reasoning performance. These findings suggest that the right IFC may be responsible for the time-pressure effect in conflicting reasoning processes. When the right IFC activity was impaired in the short-span trials in which subjects were not given sufficient time for reasoning, the subjects may rely on the fast heuristic system, which result in belief-bias responses. Tsujii & Watanabe (2010) therefore offer the first demonstration of neural correlates of time-pressure effect on the IFC activity in belief-bias reasoning.

### 2.3 Aging and belief-bias reasoning

Behavioural Tsujii et al. (2010b) examined the difference in neural activity associated with deductive reasoning processes between young and older adults. Some behavioural studies reported that older adults exhibited a larger belief-bias effect than young adults (De Neys & Van Gelder, 2009), though the neural correlates of the aging effect on belief-bias reasoning remained unknown. Therefore, Tsujii et al. (2010b) examined IFC activity differences in belief-bias reasoning between young (mean age, 21.50 years) and older subjects (mean age, 68.53 years) using fNIRS.

Behavioural analysis found that older adults exhibited a larger belief-bias than young adults. Although the belief-bias effect was significant in both age groups, the size of the effect was significantly larger for older than young adults. In the belief-bias reasoning paradigm, automatic semantic processing interferes with reasoning performance in incongruent trials. Subjects were thus required to inhibit irrelevant semantic processing to resolve the conflicting reasoning. However, it is generally known that older adults are less able to inhibit task-irrelevant information processing than young adults. This may be one of the reasons that older adults exhibited a larger belief-bias effect in deductive reasoning.

NIRS analysis showed that the right IFC was more activated than the left IFC in young adults, while there was no significant difference between the right and left IFCs in older adults. That is, hemispheric asymmetry of IFC activation (right-lateralization) was only observed in young subjects. In addition, the reduced lateralization of older adults was not due to reduction of right IFC activity, but due to enhancement of left IFC activity. These results are in line with numerous fMRI findings that showed age-related reduction of hemispheric asymmetry and over-recruitment in prefrontal activity in several tasks (Cabeza et al., 1997, 2002, 2004; Langenecker et al., 2004, 2007; Nielson et al., 2002, 2004; Rajah & McIntosh, 2008; Rympa & D'Esposito, 2000). For example, older adults often show bilateral activation in tasks associated with left-lateralized activity in young adults, such as verbal working memory and semantic processing tasks (Bergerbest et al., 2009; Rajah & McIntosh, 2008; Rympa & D'Esposito, 2000). Likewise, older adults often show bilateral activation in tasks associated with right-lateralized activity in young adults such as episodic retrieval and response inhibition tasks (Langenecker & Nielson, 2003; Nielson et al., 2002, 2004).

With regard to the function of age-related lateralization reduction, two main interpretations have been proposed: the compensatory and dedifferentiation hypotheses. The compensation hypothesis considers that older adults recruit more areas of the contralateral hemisphere than younger adults in order to achieve or attempt to achieve the same levels of performance (Reuter-Lorenz et al., 2000). In contrast, the dedifferentiation hypothesis considers that the additional recruitment reflects a generalized spreading of activity due to reduced specialization of function, regardless of whether it has a compensatory effect (Logan et al., 2002). Tsujii et al. (2010b) conducted the correlation analysis which revealed that the positive correlation between reasoning accuracy and IFC activation was significant in both hemispheres for older subjects, while a significant correlation was only found in the right hemisphere for young subjects. These findings are consistent with the compensatory hypothesis that older adults may recruit the left IFC to compensate for the age-related decline of inhibitory control functions.

### 2.4 Utility of fNIRS in reasoning studies

In the present chapter, we introduced fNIRS approach to elucidate the neural mechanisms of deductive reasoning processes, although most of the previous studies used fMRI technique (Goel et al., 2000; Goel and Dolan, 2001, 2003; Knauff et al., 2002, 2003; Monti et al., 2007, 2009; Stavy et al., 2006). Certain shortcomings of the NIRS technique thus need to be mentioned. First, NIRS can detect hemodynamic changes only at the surface of the brain (about 2 cm beneath the skull). Subcortical responses thus cannot be examined using NIRS. In particular, activity in the anterior cingulate cortex, which is known to be associated with conflict detection and is probably an important neural locus of belief-bias reasoning (Goel, 2007; De Neys et al., 2008), cannot be examined by NIRS. Second, NIRS features relatively low spatial resolution compared with fMRI, making precise analysis with it difficult.

Despite these shortcomings, use of NIRS is becoming increasingly common in recent neuroimaging studies, because of its advantages, such as exceptional safety, low cost and robustness against body movement. Indeed, recent NIRS studies have established the utility of NIRS in various cognitive tasks involving working memory (Ehlis et al., 2008; Tsujii et al. 2007, 2009b, 2010c), response inhibition (Boecker et al., 2007; Tsujii et al., 2011b), and semantic memory retrieval (Herrmann et al., 2003, 2004; Tsujii et al., 2009a). We believe that NIRS will improve understanding of the neural substrates of reasoning processes.

fNIRS is also expected to facilitate the investigation of wide subject populations, including young children (Minagawa-Kawai et al., 2008; Tsujii et al., 2009b) and the elderly (Herrmann et al., 2006; Kameyama et al., 2004). Children and elderly subjects have been found to exhibit a larger belief-bias effect than young adults (De Neys and Van Gelder, 2009). It is thus important to examine the neural mechanisms in these subject populations in reasoning research. In deed, we successfully demonstrated the hemispheric difference of IFC activity between young and older adults in the belief-bias reasoning task (Tsujii et al. 2010b). We believe that fNIRS will improve understanding of the neural substrates of reasoning processes.

## 3. TMS study in deductive reasoning

Although neuroimaging studies, such as fMRI and fNIRS, have provided useful insights of the neural mechanisms of deductive reasoning, they can only examine correlations between cortical areas and a type of behaviour. In contrast, the rTMS approach can establish the causal relationships between brain and behaviour more directly compared with fMRI and fNIRS. In our laboratory, an off-line method of rTMS was adopted to examine the neural correlates of deductive reasoning. In the off-line method, low-frequency rTMS is delivered to a specific brain area over several minutes to disrupt normal functioning of this area transiently after stimulation (see Robertson et al., 2003 for detailed review). For example, Devlin et al. (2003) delivered low-frequency (1Hz) magnetic stimulation at IFC region for 10 min and found that the semantic processing was disrupted in a semantic decision task. In the first experiment, we examine the effect of low-frequency magnetic stimulation at IFC region on performance of congruent and incongruent reasoning performance (Tsujii et al., 2010a). In the second experiment (Tsujii et al., 2011a), we investigated the effect of rTMS at SPL (superior parietal lobule) on the performance of abstract reasoning in which semantic content was lacking (e.g., "All P is B"). The stimulation sites of IFC and SPL were presented in Fig. 4.

### 3.1 The role of IFC in belief-bias reasoning

Tsujii et al. (2010a) examined the role of IFC in belief-bias reasoning using rTMS approach. Subjects participated in a belief-bias reasoning task for 10 min (pre-test), then received low-frequency (1 Hz) rTMS in the left or right IFC for 10 min, and finally performed a reasoning task again for 10 min (post-test). The reasoning task included congruent and incongruent trials. For control conditions, we used a specially designed sham coil with the same visual appearance and same audible clicking sound as the TMS coil but without production of any magnetic field. There was no significant difference between TMS and sham condition in the pre-test. Our interest was the TMS effect on performance of congruent and incongruent reasoning trials in the post-test.

We found that right IFC stimulation significantly impaired reasoning performance in incongruent but not congruent trials, enhancing the belief-bias effect. This is consistent with the findings of previous neuroimaging studies using fMRI and fNIRS. In the belief-bias reasoning paradigm, semantic information processing should interfere with reasoning performance in incongruent trial, while facilitating it in congruent trials. Subjects were therefore required to inhibit semantic processing to resolve the conflicts in reasoning. When rTMS inhibited the inhibitory function of the right IFC, subjects could not respond correctly in incongruent trials, enhancing belief-bias responses.

De Neys & Franssens (2009) recently investigated the detailed nature of the inhibition process in belief-bias reasoning. In their experiments, subjects performed a lexical decision task after solving the deductive reasoning task which involved congruent and incongruent trials. They found that incongruent reasoning delayed lexical decisions regarding the target word that were relevant to the cued heuristic beliefs. Interestingly, no significant difference was apparent between congruent and incongruent reasoning trials for unrelated words. That is, the accessibility of unrelated words was unaffected. This suggests that the inhibition process is focused in nature and is specifically targeted at cued beliefs, not at semantic processing in general.

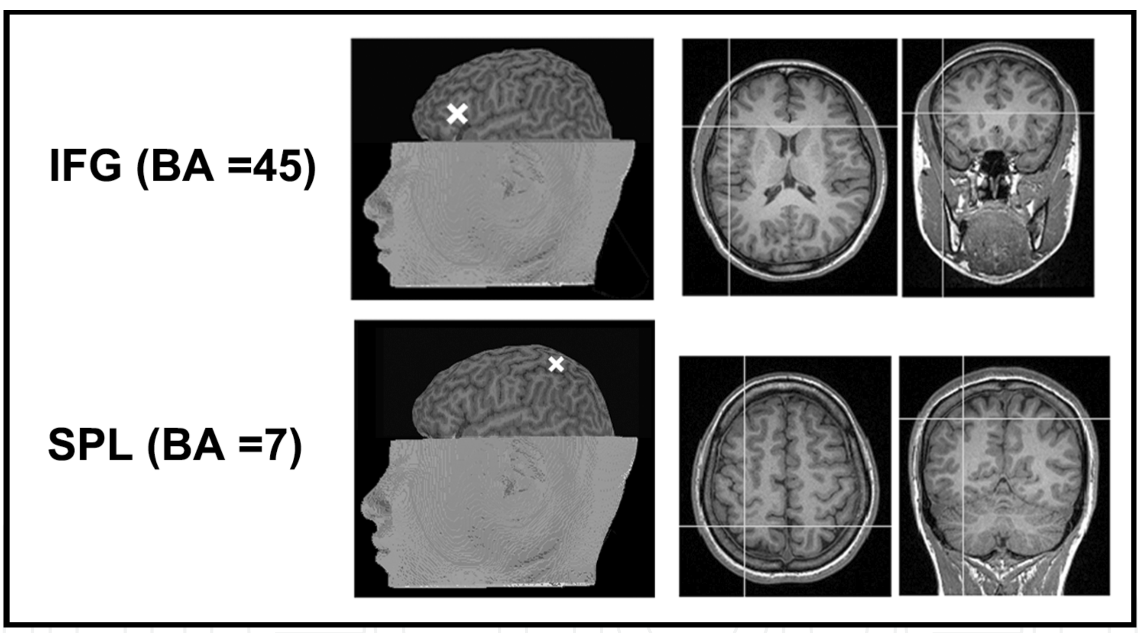


Fig. 4. Stimulation sites in rTMS experiments (IFG: inferior frontal gyrus, SPL: superior parietal lobule, BA: Broadman area).

In contrast, left IFC stimulation impaired congruent reasoning performance, while paradoxically facilitating incongruent reasoning performance. As a result, the belief-bias effect was eliminated. The left IFC is generally known to be associated with verbal or semantic processing in a wide variety of tasks, including the semantic decision task (Devlin et al., 2003), verbal fluency task (Costafreda et al., 2006), and sentence comprehension task (Zhu et al., 2009). Subjects whose left IFC was impaired by rTMS did not suffer from interference by irrelevant semantic processing, resulting in elimination of belief-bias effect. This study thus demonstrated for the first time the roles of the left and right IFC in belief-bias reasoning using an rTMS approach.

### 3.2 The role of SPL in abstract reasoning

Tsujii et al. (2011a) examined the effect of IFC stimulation on abstract reasoning trials in which semantic content was lacking (e.g. "All P are B"), as well as content reasoning trials which involved the congruent and incongruent trials. In contrast of the incongruent reasoning performance, we did not find the significant IFC stimulation effect on abstract reasoning performance. Right IFC stimulation impaired only incongruent trials. These findings suggest that the right IFC may not the neural locus of the analytic reasoning system. Rather, the right IFC may play a role in blocking the belief-based heuristic system (left IFC) in solving incongruent reasoning trials. On the other hand, individuals need not actively inhibit the heuristic processing on abstract trials, so right IFC stimulation did not significantly affect abstract reasoning trials.

So, where is the neural locus responsible for abstract reasoning performance? Tsujii et al (2011a) magnetically stimulated SPL (superior parietal lobule: BA = 7). In contrast to the IFC stimulation, bilateral SPL stimulation significantly impaired abstract reasoning performance. This is consistent with previous fMRI studies which showed that the abstract reasoning performance significantly activated the SPL region (Goel et al., 2000; Goel & Dolan, 2001; Knauff et al., 2002, 2003). In general, SPL is associated with spatial processing based on evidence from fMRI (Takahama et al., 2010; Thakral & Slotnick, 2009), neurological patients (Ferber & Danckert, 2006; Shinoura et al., 2009) and TMS studies (Hamidi et al., 2008, 2009). Some authors have claimed that cognitive processes of constructing and manipulating spatially organized mental models are essential for deductive reasoning (Johnson-Laird, 1999, 2001). The mental models are a form of representation that can be spatial but more abstract. Phenomenological reports in the reasoning literature often have suggested that subjects may solve abstract syllogisms through the use of mental images of Venn diagrams and Euler circles (Goel et al., 2000; Goel & Dolan). Stimulation of SPL may thus have impaired abstract and incongruent reasoning by disrupting spatial processing. In contrast, congruent reasoning performance where semantic-based heuristics are sufficient to solve the problem was unimpaired.

The findings are largely consistent with the dual-process theory of reasoning, which proposes the existence of two different reasoning systems in humans: a belief-based heuristic system; and a logic-based analytic system. In our study, the left IFG appears to correspond to the heuristic system, while bilateral SPLs are part of the analytic system. The right IFG may play a role in blocking the belief-based heuristic system (left IFG) in solving incongruent reasoning trials. So, our rTMS study could offer an insight about functional roles of distributed brain systems in human deductive reasoning by utilizing the rTMS approach.

## 4. Conclusion

In the present chapter, we briefly reviewed recent neuroimaging studies of human deductive reasoning, especially focusing on relatively new imaging technique: functional near-infrared spectroscopy (fNIRS) and repetitive transcranial magnetic stimulation (rTMS). A series of studies in our laboratory successfully provided evidence which is consistent with recent dual-process theory of reasoning. The dual-process theory proposed belief-based heuristic system and a logic-based analytic system. The heuristic system is assumed to operate rapidly and automatically, whereas operations of the analytic system are believed to be slow and demanding of computational resources. Our fNIRS findings could demonstrate the attention-demanding and time-consuming properties of the right IFC activities. In addition, our rTMS studies showed that the left IFG appears to correspond to the heuristic system, while bilateral SPLs are part of the analytic system. The right IFG may play a role in blocking the belief-based heuristic system (left IFG) in solving incongruent reasoning trials. Although there are several limitations of fNIRS and rTMS, we believe they are useful to examine the neural substrates of logical reasoning process.

## 5. Acknowledgment

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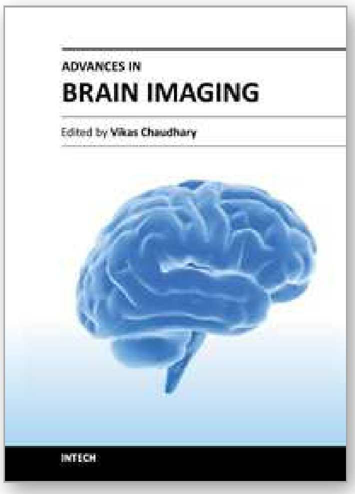


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Remarkable advances in medical diagnostic imaging have been made during the past few decades. The development of new imaging techniques and continuous improvements in the display of digital images have opened new horizons in the study of brain anatomy and pathology. The field of brain imaging has now become a fast-moving, demanding and exciting multidisciplinary activity. I hope that this textbook will be useful to students and clinicians in the field of neuroscience, in understanding the fundamentals of advances in brain imaging.