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The role of inferior frontal cortex in belief-bias reasoning: An rTMS study☆

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ABSTRACT

The belief-bias effect in syllogistic reasoning refers to the tendency for subjects to be erroneously biased when logical conclusions are incongruent with belief about the world. This study examined the role of inferior frontal cortex (IFC) in belief-bias reasoning using repetitive transcranial magnetic stimulation (rTMS). We used an off-line rTMS method to disrupt IFC activity transiently. Right IFC stimulation significantly impaired incongruent reasoning performance, enhancing the belief-bias effect. Subjects whose right IFC was impaired by rTMS may not be able to inhibit irrelevant semantic processing in incongruent trials. Although left IFC stimulation impaired congruent reasoning, it paradoxically facilitated incongruent reasoning performance, eliminating the belief-bias effect. Subjects whose left IFC was impaired by rTMS may not suffer from interference by irrelevant semantic processing. This study demonstrates for the first time the roles of left and right IFC in belief-bias reasoning using an rTMS approach.

1. Introduction

Neuroimaging studies of deductive reasoning are attracting increased interest in recent cognitive science (Goel, 2007). Deductive reasoning is the process of drawing valid conclusions from a given set of premises. Although deductive reasoning 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 judgments. This tendency toward bias in human reasoning has been experimentally studied through the demonstration of belief-bias effect in syllogistic reasoning (Evans, 2008).

Belief-bias effect refers to the tendency of subjects to be more likely to accept the conclusion of a syllogism if they find it believable than if they disbelieve it, irrespective of its actual logical validity (Evans, 2008). A typical design is illustrated in Fig. 1(a), and includes two types of syllogisms: one is a congruent syllogism, in which the logical conclusion is consistent with beliefs about the world (valid-believable and invalid-unbelievable), while the other is an incongruent syllogism, in which the logical conclusion is inconsistent with beliefs (valid-unbelievable and invalid-believable). Belief-bias in semantic processing thus facilitates logical responses in congruent trials, while it inhibits logically correct responses in incongruent trials.

Recent neuroimaging studies have examined the neural correlates of belief-bias reasoning (Goel, 2007). These studies demonstrated that avoiding belief-bias effect was associated with right inferior frontal cortex (IFC) activity, using functional magnetic resonance imaging (fMRI; Goel & Dolan, 2003) and functional near-infrared spectroscopy (fNIRS; Tsujii & Watanabe, 2009; Tsujii & Watanabe, 2010; Tsujii, Yamamoto, Masuda, & Watanabe, 2009; Tsujii, Okada, & Watanabe, in press-a; Tsujii, Yamamoto, Ohira, Takahashi, & Watanabe, in press-b). Right IFC activity was enhanced when subjects could respond correctly to incongruent reasoning trials (De Neys, Vartanian, & Goel, 2008; Goel & Dolan, 2003). In addition, recent fNIRS studies found that subjects with enhanced right IFC activity performed better in incongruent reasoning trials (Tsujii & Watanabe, 2009; Tsujii & Watanabe, 2010). The authors of these studies claimed that the right IFC plays a role in inhibiting the semantic processes which could interfere with correct logical reasoning in incongruent trials.

In contrast, left IFC activity was enhanced when subjects performed belief-congruent reasoning trials (Goel, Buchel, Frith, & Dolan, 2000; Goel, Stollstorff, Nakic, Knutson, & Grafman, 2009; Goel & Dolan, 2003). The left IFC is generally known to be associated with verbal or semantic information processing (e.g. Costafreda et al., 2006). Semantic processing by the left IFC could facilitate congruent reasoning, while interfering with incongruent reasoning performance. Although these findings are important, neuroimaging studies can only examine the correlation between area of cortex and a type of behavior.

☆ This study was carried out in CARLS, Keio University, Mita 3-1-7, Minato-ku, Tokyo 108-0073, Japan.

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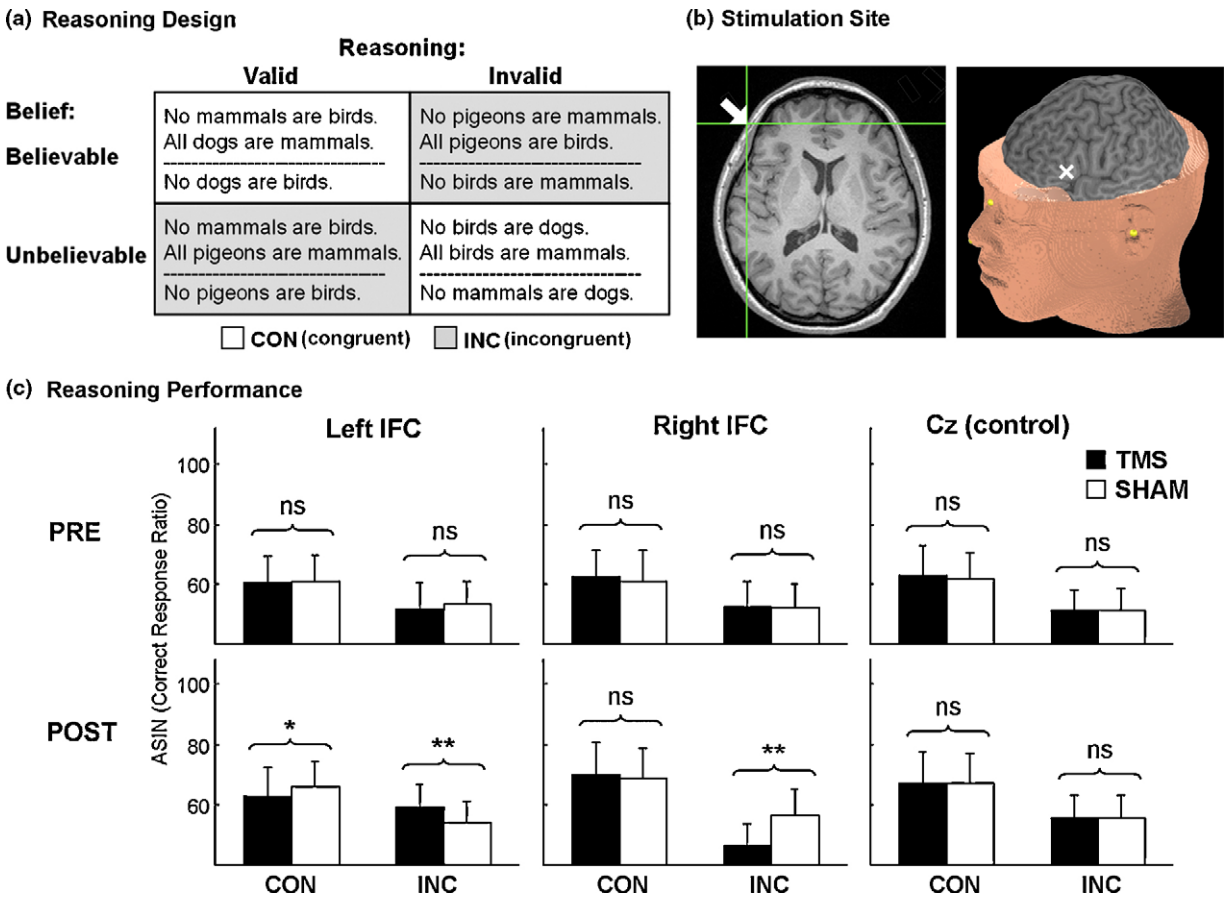

Fig. 1. (a) Design of the present experiment. Two types of reasoning trials were prepared, congruent (CON) and incongruent (INC). In the actual experiment, we presented syllogisms to subjects in Japanese. (b) The sites of stimulation in the present TMS study were the left and right inferior frontal cortex (IFC). More specifically, we stimulated the pars triangularis (BA 45). The left photograph shows a transverse MRI image and the right a 3D model created with a frameless stereotaxic system (Brainsight, Rouge Research Inc., Montreal, Quebec, Canada). (c) Accuracy scores for congruent and incongruent reasoning trials in the left IFC, right IFC, and Cz stimulation groups ($^{*}p < 0.05$; $^{**}p < 0.01$).

The aim of this study was to examine the roles of IFC in belief-bias reasoning using repetitive transcranial magnetic stimulation (rTMS). This technique has been used to establish causal relationships between brain and behavior (Pascual-Leone, Walsh, & Rothwell, 2000). 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 (Robertson, Theoret, & Pascual-Leone, 2003). In the present study, 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). We hypothesized that left IFC stimulation would reduce the belief-bias effect by inhibiting irrelevant semantic processing, while, in contrast, right IFC stimulation would enhance the belief-bias effect by impairing inhibition of irrelevant semantic processing.

2. Methods

2.1. Subjects

The subjects were 72 healthy Japanese volunteers (39 females, 33 males) aged 22.96 ± 3.49 (range, 20–37) years. The Edinburgh Handedness Inventory (Oldfield, 1971) indicated that 67 of the subjects were right-handed. All subjects had normal or corrected-to-normal vision. None had received any formal training in logic. The study was conducted in accordance with the principles of the Declaration of Helsinki and the guidelines from the international workshop on the safety of TMS (Wassermann, 1998), and the protocol was approved by the Ethics Committee of Keio University. Written informed consent was obtained from all subjects prior to enrolment in the study. Twenty-four subjects received TMS in the left IFC, 24 in the right IFC, and the other 24 at the Cz site of the International 10–20 system (vertex).

2.2. Reasoning task

We prepared 128 syllogisms. The combination of logical validity and believability of conclusion yielded two types of trials (Fig. 1a), comprising 64 congruent trials (32 valid-believable, 32 invalid-unbelievable) and 64 incongruent trials (32 valid-unbelievable, 32 invalid-believable). Believability of conclusion was rated by 5 independent subjects prior to the experiment using a seven-point questionnaire (1 = completely unbelievable, 7 = completely believable). Mean believability scores were 6.56 for believable syllogisms (SD = 0.57) and 1.57 for unbelievable syllogisms (SD = 0.53). Half of the syllogisms consisted only of universal arguments (e.g. all dogs are mammals, no dogs are birds) while the other half involved particular arguments (e.g. some mammals are dogs, some birds are not dogs), the number of which was counter-balanced for each condition.

Each subject visited our laboratory twice: once for TMS and once for SHAM stimulation. Half of the subjects participated in the TMS first, and the other half the SHAM stimulation first. For each visit, subjects performed a reasoning task twice, first pre-test (10 min), immediately before stimulation, and then post-test (10 min), immediately after stimulation. Each test was comprised of 32 syllogisms (16 congruent, 16 incongruent). We presented subjects with a booklet in which 32 syllogisms were printed. They were asked to respond to the validity of each syllogism by writing their evaluation in a response sheet. The instructions emphasized that the premises should be assumed to be true and that a conclusion should be accepted only if it follows logically from the premises.

2.3. rTMS stimulation

The location of coil placement was determined using an MRI-image-guided stereotaxic system (Brainsight, Rouge Research Inc., Montreal, Quebec, Canada) and individual high-resolution T1-weighted MRI images of each participant. This system