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Neural correlates of belief-bias reasoning under time pressure: A near-infrared spectroscopy study

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ABSTRACT

The dual-process theory of reasoning explained the belief-bias effect, the tendency for human reasoning to be erroneously biased when logical conclusions are incongruent with belief about the world, by proposing a belief-based fast heuristic system and a logic-based slow analytic system. Although the claims were supported by behavioral findings that the belief-bias effect was enhanced when subjects were not given sufficient time for reasoning, the neural correlates were still unknown. The present study therefore examined the relationship between the time-pressure effect and activity in the inferior frontal cortex (IFC) during belief-bias reasoning using near-infrared spectroscopy (NIRS). Forty-eight subjects performed congruent and incongruent reasoning tasks, involving long-span (20 s) and short-span trials (10 s). Behavioral 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. We therefore offer the first demonstration of neural correlates of time-pressure effect on the IFC activity in belief-bias reasoning.

Introduction

Neuroimaging studies of deductive reasoning have become one of the major issues 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, although they can also bias our judgments. This tendency towards bias in human reasoning has been experimentally studied through the demonstration of the belief-bias effect in syllogistic reasoning (Evans, 2003; Klauer et al., 2000; Luo et al., 2008).

The 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 rather than if they find it unbelievable, irrespective of its actual logical validity (Evans, 2003; Klauer et al., 2000). A typical design is illustrated in Fig. 1a and includes two types of syllogisms: one is congruent syllogism, in which the logical conclusion is consistent with beliefs about the world (valid-believable and invalid-unbelievable), the other is incongruent syllogism, in which the logical conclusion is inconsistent with beliefs (valid-unbelievable and invalid-believable). Belief-bias thus facilitates logical responses in congruent trials, while it inhibits logically correct responses in incongruent trials.

One explanation for the belief-bias effect is offered by the dual-process theory of reasoning (De Neys, 2006a; Evans, 2008; Osman and Stavy, 2006; Stanovich and West, 2000), which proposes the existence of two different human reasoning systems. 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 heuristic default system is assumed to operate rapidly and automatically, whereas operations of the analytic system are believed to be slow and demanding of computational resources (Evans, 2008; De Neys, 2006b; De Neys and Glumicic, 2008; Reverberi et al., 2009). The dual-process theory claims that the belief-bias effect should be enhanced when the analytic system could not inhibit the automatic operations of the heuristic system, especially under dual-task and time-pressure conditions (De Neys, 2006a,b; Evans and Curtis-Holmes, 2005; Evans et al., 2009).

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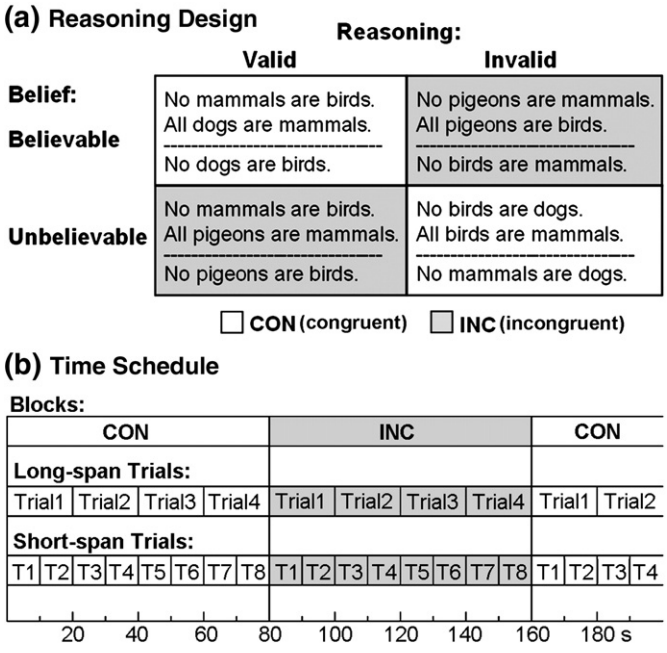

Fig. 1. (a) Design of the present experiment. Two types of reasoning trials were prepared, congruent (CON) and incongruent (INC). In the actual experiment, we presented syllogisms to subjects in Japanese. (b) Time schedule of the congruent and incongruent reasoning trials in the long-span (20 s) and short-span conditions (10 s).

This study addressed the difference in speed between the heuristic and analytic reasoning systems. Although behavioral studies found that the belief-bias effect was enhanced when subjects were not given sufficient time for reasoning (Evans and Curtis-Holmes, 2005; Evans et al., 2009; Roberts and Newton, 2001), the neural correlates of the time-pressure effect was still unclear. Recent 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 and 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 and Dolan, 2003). However, since these studies did not manipulate the time-span of reasoning trials, it is still unclear how time-pressure modulates the IFC activity in reasoning processes.

We therefore examined the neural correlates of the time-pressure effect on the IFC activity in belief-bias reasoning using near-infrared spectroscopy (NIRS). NIRS is a relatively new imaging technique for investigating cortical hemodynamic responses by measuring changes in the attenuation of near-infrared light passing through tissue (Koizumi et al., 2003; Maki et al., 1995, 1996; Shalinsky et al., 2009). 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.

Recently, Tsujii and Watanabe (2009) have introduced the NIRS technique into reasoning studies. They examined the dual-task effect on IFC activity in belief-bias reasoning. Tsujii and Watanabe (2009) found that attention-demanding secondary tasks impaired the right IFC activity during incongruent reasoning trials, enhancing the belief-bias responses in behavioral performance. They concluded that the right IFC activity was critical to resolving conflicting reasoning but was attention-demanding. So, when a demanding secondary task impaired the right IFC activity, subjects could not inhibit the automatic heuristic system to enable analytic system activity, resulting in an enhanced belief-bias effect. Although they could successfully demonstrate the neural correlates of dual-task effect in belief-bias reasoning, it is still unclear how time-pressure modulates the IFC activity because they did not manipulate the time-span of reasoning trials.

In the present study, 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). It is already known that the belief-bias effect should be enhanced in the short-span trials based on previous behavioral studies (Evans and Curtis-Holmes, 2005), and that the right IFC activity should be enhanced when subjects perform incongruent reasoning trials compared with congruent ones, based on previous neuroimaging findings (De Neys et al., 2008; Goel and Dolan, 2003; Tsujii and Watanabe, 2009). Our main interest was in determining how the right IFC activity is affected by the manipulation of time-span in belief-bias reasoning tasks. We hypothesized that the right IFC activity would be reduced in short-span compared with long-span tasks, enhancing the belief-bias responses in behavioral performance.

Methods

Subjects

The subjects were 48 healthy Japanese volunteers (30 females and 18 males) aged 22.56 ± 4.04 (range, 19–34) years. The Edinburgh Handedness Inventory (Oldfield, 1971) was used to classify 45 subjects as 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 protocol was approved by the Ethics Committee at Keio University. Written informed consent was obtained from all subjects prior to enrolment in the study. All were in good health and without any significant clinical history of physical or mental illness, and none were receiving any medication likely to interfere with the study results.

Materials

We prepared 96 syllogisms. A combination of logical validity and believability of conclusions yielded two types of trials (Fig. 1a), comprising 48 congruent trials (24 valid-believable, 24 invalid-unbelievable) and 48 incongruent trials (24 valid-unbelievable, 24 invalid-believable). The believability of the conclusion was rated by five independent subjects prior to the experiment using a seven-point questionnaire (1 = completely unbelievable, 7 = completely believable). Mean believability scores were 6.48 for believable syllogisms (SD = 0.50; range, 5.2–7.0) and 1.61 for unbelievable syllogisms (SD = 0.58; range, 1.0–2.8). Half of the syllogisms consisted only of universal arguments (e.g. all dogs are mammals, no dogs are birds), while the other half involved specific arguments (e.g. some mammals are dogs, some birds are not dogs), which were counter-balanced for each congruency (congruent and incongruent) and time-span (long and short) condition.

Procedures

The experiment was performed separately for each individual. There were two runs in the present experiment: one for the long-span condition and the other for the short-span condition. Each run took about 12 min. Subjects could take a short break between the first and