Biological Psychology 103 (2014) 276–282

Contents lists available at ScienceDirect

Biological Psychology

journal homepage: www.elsevier.com/locate/biopsycho

The neural correlates of belief-bias inhibition: The impact of logic training

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ARTICLE INFO

Article history:
Received 6 January 2014
Accepted 18 September 2014
Available online 27 September 2014

Keywords:
Dual-process
Belief-bias
Logical training
Inhibition
Event-related fMRI

ABSTRACT

Functional Magnetic Resonance Imaging (fMRI) was used to investigate the brain activity associated with response change in a belief bias paradigm before and after logic training. Participants completed two sets of belief biased reasoning tasks. In the first set they were instructed to respond based on their empirical beliefs, and in the second – following logic training – they were instructed to respond logically. The comparison between conflict problems in the second scan versus in the first scan revealed differing activation for the left inferior frontal gyrus, left middle frontal gyrus, cerebellum, and precuneus. The scan was time locked to the presentation of the minor premise, and thus demonstrated effects of belief–logic conflict on neural activation earlier in the time course than has previously been shown in fMRI. These data, moreover, indicated that logical training results in changes in brain activity associated with cognitive control processing.

1. Introduction

When we discuss sports, politics or religion our beliefs have an influence on the arguments we are willing to accept. Beliefs (in this context our empirical knowledge about the world) have also been shown to have a profound effect on the inferences that people make in the lab (Evans, Barston, & Pollard, 1983). In deductive reasoning (the process of inferring logically valid conclusions from premises), the belief-bias effect is that reasoners typically accept more believable conclusions than unbelievable conclusions, but also accept more logically valid conclusions than invalid. These factors interact such that performance on problems where belief and logic are consistent is superior to belief-neutral problems, however, participants have considerable difficulty where there is a belief–logic conflict (Evans, 2003; Klauer, Musch, & Naumer, 2000; Stupple, Ball, Evans, & Kamal-Smith, 2011). Dual-process theories attempt to explain the observed phenomenon by proposing two types of cognitive process underlying belief-bias (De Neys, 2006a, 2006b; Evans, 2003, 2007, 2008; Osman & Stavy, 2006; Stanovich & West, 2000). Type 1 processing, entails rapid belief-driven heuristics; whereas, Type 2 processing, entails slower analytic responding (Evans, 2003, 2007). Where there is a belief–logic conflict these fast and slow processes compete, with slower responses correlating with increased logical responding (Stupple & Ball, 2008; Stupple et al., 2011; Thompson, Striemer, Reikoff, Gunter, & Campbell, 2003).

Dual-process theories such as these have been investigated through many behavioral studies, which have identified some basic principles of the two cognitive processes. For example, studies have demonstrated robust effects of response patterns, response times (increased response times to problems where logic and belief are in conflict), and confidence ratings (feelings of 'rightness' predict rethinking times to reach logical conclusions) within the belief-bias paradigm (Evans et al., 1983; Prowse Turner & Thompson, 2009; Stupple & Ball, 2008) which are well explained by dual-process accounts. Moreover, De Neys (2006b) demonstrated reductions in logical responding for conflict problems when participants were under a concurrent working memory load, while Evans and Curtis-Holmes (2005) demonstrated increased belief driven responses under a rapid response condition. There is also a wealth of

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http://dx.doi.org/10.1016/j.biopsycho.2014.09.010
0301-0511/

individual differences data that indicate thinking dispositions and working memory are supportive of dual process accounts of many higher level cognitive tasks (e.g., Stanovich & West, 2000). Neuroscientific methods, such as fMRI, functional near infrared spectroscopy (fNIRS), repetitive transcranial magnetic stimulation (rTMS), and event-related potentials (ERPs) have made a valuable contribution to the area, demonstrating a range of findings consistent with the predictions of dual process theory (Banks & Hope, 2014; Goel & Dolan, 2003; Luo et al., 2008, 2013b; Luo, Yang, Du, & Zhang, 2010; Tsujii & Watanabe, 2009, 2010; Tsujii, Masuda, Akiyama, & Watanabe, 2010; Tsujii, Okada, & Watanabe, 2010; Tsujii, Sakatani, Masuda, Akiyama, & Watanabe, 2011).

Using fMRI, researchers (Goel & Dolan, 2003; Goel, Buchel, Frith, & Dolan, 2000) have found that the belief-bias effect is associated with increased activation of the right lateral prefrontal cortex (PFC). Tsujii and colleagues have also found the right lateral PFC was enhanced when participants gave logical responses to belief–logic conflict problems, thus corroborating fMRI studies with evidence from fNIRS and rTMS methodologies (Tsujii & Watanabe, 2009, 2010; Tsujii, Masuda, Akiyama, & Watanabe, 2010; Tsujii, Okada, & Watanabe, 2010; Tsujii et al., 2011). Although the right lateral PFC appears to be activated by belief–logic conflict, participants in these studies (Goel & Dolan, 2003; Tsujii & Watanabe, 2009, 2010; Tsujii, Masuda, Akiyama, & Watanabe, 2010; Tsujii, Okada, & Watanabe, 2010; Tsujii et al., 2011) did not receive any formal training in logic – in fact, participants are usually selected on the basis of having had no training in formal logic. Using positron emission tomography (PET) to compare brain activity in trials before and after logical training (i.e., training people to inhibit matching bias), Houdé and colleagues (2000) found that the left-prefrontal network and right ventromedial prefrontal cortex were engaged when participants successfully overcome matching bias in the Wason Selection Task. However, previous studies have not yet demonstrated whether effects of logical training can induce a similar change in reasoning strategy and neural activity in the belief bias paradigm. According to the results of previous studies, the reasoning process can start as soon as the premises are presented (Fangmeier, Knauff, Ruff, & Sloutsky, 2006; Luo et al., 2010, 2008; Qiu et al., 2007), however, most fMRI studies have primarily focused on conclusion processing instead of on the processing of premises (Bonnefond & der Henst, 2009). Therefore, it is important to examine the processing of the premises using fMRI to test for corroborating evidence of belief–logic conflict effects at this early stage in premise presentation.

To determine how brain functions change with logical training in belief-biased reasoning and to contribute to the discussion contrasting functional neuroanatomy and neuropedagogy (Goel, 2008; Houdé, 2008), we conducted an fMRI study in which the participants were scanned both before and after logical training. In the first scan, participants were required to respond to the belief-biased items (both conflict problems and non-conflict problems) in accordance with their empirical beliefs, however, in the second scan participants were required to respond in accordance with logic. It was hypothesized that the logical training would exert greater influence on the conflict problems, because the participants would need to inhibit their belief-driven responding and engage in analytic processing.

The present study aimed to determine (1) whether the pattern of brain activation associated with overcoming belief-bias through logical training is same as that of without logical training (Goel & Dolan, 2003), (2) whether Houdé et al.'s (2000) matching bias effect can be extended to a belief bias paradigm, and (3) whether these effects are observable earlier in the presentation of premises stimuli than has previously been shown in fMRI. Based on the previous studies (Goel & Dolan, 2003; Houdé et al., 2000), it was hypothesized that the processing of reasoning in the second scan versus in the first scan will activate regions in the right lateral PFC and the left-prefrontal network (i.e., left inferior frontal gyrus). The supposition is that this contrast would be related to belief-bias inhibition after logical training. Most importantly, the extent to which the cortical systems underlying belief bias are plastic with respect to logical training was examined.

Table 1
Sample item of the study.

Non-conflict problems	Encompassing MT, DA, MP, and AC reasoning forms Take **MT** form for example: **Major premise:** If a number can be divided by 2, then it is an even number **Minor premise:** The number is not an even number **Option 1:** The number can be divided by 2 **Option 2:** The number cannot be divided by 2 (**Logic and Belief-based response**) **Option 3:Whether** the number can or not be divided by 2 is uncertain Take **MP** form for example: **Major premise:** If one's answer is correct, then he will get score **Minor premise:** Somebody whose answer is correct **Option 1:** The person got score (**Logic and Belief-based response**) **Option 2:** The person did not get score **Option 3:Whether** the person got score or not is uncertain
Conflict problems	Encompassing MT, DA, MP, and AC reasoning forms Take **DA** form for example: **Major premise:** If the ball is thrown into the basket, then the point will be scored **Minor premise:** The ball was not thrown **Option 1:** The point was scored **Option 2:** The point was not scored (**Belief-based response**) **Option 3:** Whether the point was scored or not is uncertain (**Logic-based response**) Take **AC** form for example: **Major premise:** If somebody did not pass the exam, then he should make-up **Minor premise:** Somebody was given a make-up examination **Option 1:** The person passed the exam (**Belief-based response**) **Option 2:** The person did not pass the exam **Option 3:It** is uncertain whether the person passed the exam or not (**Logic-based response**)

2. Methods

2.1. Participants

Sixteen university students (eight men, aged 20–28 years; mean = 23.8 years; eight women, aged 20–26 years; mean = 23.0 years) from China were paid for their participation. They were selected on the basis of offering a belief-biased response to at least 70% of conditional reasoning problems where belief and logic conflicted (see Table 1) during a pre-test. All participants were right-handed, and with no reported neurological disorders, significant physical illness, head injury, or alcohol/drug abuse. This study was approved by the local ethics committee of Shanghai Normal University, and all participants signed an informed consent form prior to their inclusion in the experiment.

2.2. Design and stimuli

This study was organized into a 2×2 design. The first factor was the type of problem (see Table 1), consisting of 2 levels, conflict problems (in which the logical conclusion is inconsistent with one's beliefs) and non-conflict problems (in which the logical conclusion is consistent with one's beliefs). The second factor was logical training, consisting of 2 levels: naive participants prior to logical training and then post logic training. Specifically, participants were first required to perform the reasoning task without any logical training and were instructed to draw a conclusion based on their existing knowledge (or empirical beliefs) in the first scan, and were then asked to draw a conclusion based on logical rule after receiving a logical training in the second scan. Four conditions of stimuli were used in the experiment, namely belief-based instructions for non-conflict problems (BNC), belief-based instructions