Evidence for Spinozan "Unbelieving" in the Right Inferior Prefrontal Cortex

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Abstract

■ Humans can think about possible states of the world without believing in them, an important capacity for high-level cognition. Here, we use fMRI and a novel "shell game" task to test two competing theories about the nature of belief and its neural basis. According to the Cartesian theory, information is first understood, then assessed for veracity, and ultimately encoded as either believed or not believed. According to the Spinozan theory, comprehension entails belief by default, such that understanding without believing requires an additional process of "unbelieving." Participants (n = 70) were experimentally induced to have beliefs, desires, or mere thoughts about hidden states of the shell game (e.g., believing that the dog is hidden in the upper right corner). That is, participants were induced to have specific "propositional attitudes" toward specific "propositions" in a controlled way. Consistent with the Spinozan theory, we found that thinking about a proposition without believing it is associated with increased activation of the right inferior frontal gyrus. This was true whether the hidden state was desired by the participant (because of reward) or merely thought about. These findings are consistent with a version of the Spinozan theory whereby unbelieving is an inhibitory control process. We consider potential implications of these results for the phenomena of delusional belief and wishful thinking. ■

INTRODUCTION

In 2015, ecologists working off the coast of Bali discovered a species of aquatic snake that uses electricity to stun its prey, much as electric eels do. The previous sentence is false. There are no such snakes. However, for a moment, you likely believed in them. What changed in your brain when you went from believing in electric snakes to merely thinking about them?

As this example illustrates, humans can represent an idea about the world ("There are electric snakes near Bali") as something that is true, false, possibly true, preferably true, or, in this case, merely as an idea. These distinct ways of relating to ideas are known as "propositional attitudes" (McKay & Nelson, 2014). Our focus here is on the distinction between representing an idea, or "proposition," as true (believing), and representing an idea without believing that it is true. It is unknown whether the ability to entertain ideas without believing in them is an ability we share with other animals. In humans, however, this ability is likely essential for high-level cognitive functions such as planning under conditions of uncertainty and hypothesis testing, whether in science or everyday life. Furthermore, the inability to prevent one's mere thoughts from becoming beliefs may underlie mental disorders involving delusion, such as schizophrenia (Bronstein, Pennycook, Bear, Rand, & Cannon, 2019; Bear, Fortgang, Bronstein, & Cannon, 2017; Dudley, Taylor, Wickham, & Hutton, 2016; Evans, Averbeck, & Furl, 2015; Moritz & Woodward, 2005).

Beliefs are central to human cognition, but the mechanisms that distinguish belief from mere representation have received surprisingly little attention. It is worth pausing, then, to distinguish the present project from relevant research that is likely more familiar. There has been extensive research on how humans represent the beliefs of others ("mentalizing" or "theory of mind"; e.g., Decety & Lamm, 2007; Saxe & Baron-Cohen, 2006; Saxe & Kanwisher, 2003) as well as how people represent their own beliefs (a form of "metacognition"; e.g., Mazzoni & Nelson, 1998; Metcalfe & Shimamura, 1994). There is also considerable research on the representation of probability and uncertainty about states of the world (e.g., Delgado, Miller, Inati, & Phelps, 2005; Glimcher, 2003; Critchley, Mathias, & Dolan, 2001), which can be understood as the encoding of degrees of belief. Finally, as indicated above, perception typically results in belief, and memory enables the retention of beliefs. As the foregoing suggests, beliefs are cognitively ubiquitous, so much so that one might question whether belief per se can be a meaningful cognitive topic. In our view, it is not so much belief that is a distinct and underappreciated topic, but rather the ability to represent ideas without believing them.

Here, we study this ability using functional neuroimaging and a novel behavioral task, inspired by the street-side

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"shell game." Our shell game involves objects hidden in various locations, and participants can be systematically induced to have beliefs, desires, or mere thoughts about where the hidden objects are. Critically, this gives us experimental control over participants' propositional attitudes, and that, in turn, enables us to dissociate propositional attitudes from propositional content. This degree of experimental control distinguishes the shell game from prior paradigms used to study the neural mechanisms of belief and/or desire. This task also avoids confounds related to metacognition, perception, and memory. We use this method to test two cognitive models of belief, each with a long history (Gilbert, Tafarodi, & Malone, 1993; Gilbert, 1991).

According to the seventeenth century philosopher René Descartes, ideas are first comprehended and then assessed for truth, such that ideas deemed true are subsequently encoded as beliefs (Mandelbaum, 2014; Gilbert, 1991; Descartes, 1984). Descartes' contemporary, Baruch Spinoza, proposed an alternative theory. Spinoza argued that comprehension entails belief by default, implying that understanding without believing requires an additional step—a process we call "unbelieving" (Mandelbaum, 2014; Gilbert, 1991; Spinoza, 1677/1982). This could involve tagging ideas as not (necessarily) true or it could require inhibiting belief processes. The Cartesian theory, by contrast, posits no distinctive extra step for non-belief. It requires only that our brains somehow encode the epistemic status of representations as beliefs or non-beliefs, with varying degrees of certainty. We now discuss the evidence for each of these theories.

Spinozan Belief

Evidence for the Spinozan view of belief comes primarily from the phenomenon of truth bias—the default tendency to encode information as true (Vrij, 2008; Bond & DePaulo, 2006; Levine, Park, & McCornack, 1999). People are influenced by false information even when the information is explicitly presented as false (Thorson, 2015; Guenther & Alicke, 2008; Schul & Burnstein, 1985; Anderson, 1983; Anderson, Lepper, & Ross, 1980). People also remember false information as true more often than the reverse (Peter & Koch, 2016). Critically, truth bias appears to be magnified under cognitive load and time pressure (Gilbert et al., 1993; Gilbert, Krull, & Malone, 1990), suggesting that non-belief rather than belief requires additional cognitive effort. Further support for the Spinozan view comes from the illusory truth effect, whereby prior exposure to an idea makes it seem more true (Dechêne, Stahl, Hansen, & Wänke, 2010; Begg, Anas, & Farinacci, 1992). The illusory truth effect is diminished by critical engagement and increased by more superficial processing (Hawkins & Hoch, 1992). These findings support Spinoza's speculation that belief is an automatic consequence of comprehension and that understanding something without believing it requires an additional, cognitively demanding process of "unbelieving."

The behavioral evidence described above suggests that entertaining ideas without believing them may require cognitive control and therefore may recruit control-related brain regions such as the dorsolateral pFC, frontopolar cortex, inferior frontal gyrus (IFG), and anterior cingulate cortex (Niendam et al., 2012; Aron, Behrens, Smith, Frank, & Poldrack, 2007; Cole & Schneider, 2007; Chein & Schneider, 2005). Consistent with this, participants tasked with evaluating the veracity of statements exhibit increased activity in the frontopolor cortex when considering false (vs. true) statements (Marques, Canessa, & Cappa, 2009). Furthermore, evaluating statements as false is associated with reduced activation in the ventral medial prefrontal cortex (vmPFC; Harris et al., 2009; Harris, Sheth, & Cohen, 2008). The vmPFC is part of the default mode network, which typically exhibits reduced activity when people engage in cognitively demanding tasks (Gusnard, Akbudak, Shulman, & Raichle, 2001; Mazoyer et al., 2001). This reduction in vmPFC activity for rejected statements could, then, potentially result from the inhibition of a belief-related process. Likewise, individuals with damage to the vmPFC are more likely than control participants (both healthy controls and those with damage outside the frontal cortex) to believe misleading advertisements, even when the advertisements include a disclaimer about their falsehood (Asp et al., 2012). Again, this is consistent with the idea that the vmPFC is implicated in controlling or inhibiting belief.

In the neuroimaging and patient studies described above, participants explicitly reported on what they did or did not believe. Thus, it is unclear whether the observed neural responses reflect the participants' beliefs (or non-belief) or whether these responses instead reflect the metacognitive processes involved in reporting on beliefs. Avoiding this problem, Goel and Dolan (2003) examined the neural mechanisms of belief without having participants explicitly reflect or report on their beliefs. Participants evaluated the quality of arguments in which the conclusions were either consistent with the participants' beliefs or not. The authors found increased activation in the right IFG when participants correctly accepted valid arguments with conclusions that violated their beliefs (e.g., "No harmful substances are natural; All poisons are natural; [therefore] No poisons are harmful"), than when they failed to accept such arguments. More recent follow-up research found that repetitive transcranial magnetic stimulation to the right IFG increased the likelihood that participants accepted invalid arguments when the components conformed to their beliefs (Tsujii, Sakatani, Masuda, Akiyama, & Watanabe, 2011; Tsujii, Masuda, Akiyama, & Watanabe, 2010). In each of these studies, however, belief was confounded with propositional content. In other words, whether participants believed what they read depended on the plausibility of what they were reading. Although this is to be expected in everyday life, it poses a challenge for studies aiming to understand the neural mechanisms of belief. Such designs leave open the possibility that neural activity associated with belief reflects the contents of relatively believable propositions rather than the mental process of believing.

The Spinozan view raises parallel questions about a different propositional attitude, namely, *desire*. One can (and often does) desire that something be true without believing that it is true. Nevertheless, a strong form of the Spinozan theory predicts that desiring that something be true will, by default, generate a belief that it *is* true, such that this belief will persist if it is not overridden. In other words, the Spinozan theory, in addition to explaining our susceptibility to phenomena such as the illusory truth effect (which applies to neutral content), may also explain our susceptibility to *wishful thinking* (Mandelbaum, 2014; Windschitl, Scherer, Smith, & Rose, 2013; Aue, Nusbaum, & Cacioppo, 2012; Krizan & Windschitl, 2009; Babad, 1997). Consistent with this, there is some evidence that wishful thinking occurs automatically (Cahill, 2015).

Cartesian Belief

In contrast to the Spinozan view of belief as the representational default, the Cartesian view posits that information is first understood, then subsequently assessed for veracity, and ultimately encoded as either believed or not believed (with varying degrees of confidence; Gilbert, 1991; Descartes, 1984). Some advocates of the Cartesian view argue that the effect of cognitive load on truth bias can be explained as an effect of increased uncertainty, rather than the automaticity of belief (Street & Kingstone, 2017). They find that the effect of time pressure on the tendency to report false statements as true disappears when participants can respond that they are uncertain of the statement's truth value (Street & Kingstone, 2017; Street & Richardson, 2015). If belief is automatic, then cognitive load or time pressure should increase reports of belief, regardless of whether the alternative response is "false" or "not sure." By contrast, if what is automatically engaged is a Cartesian truth-assessment process, then time pressure or increased load should increase reports of uncertainty (Street & Kingstone, 2017).

Other research raises doubts about the Spinozan theory by questioning the necessity of cognitive load or time pressure to evoke truth bias (Fiedler, Armbruster, Nickel, Walther, & Asbeck, 1996; Fiedler, Walther, Armbruster, Fay, & Naumann, 1996). Participants more often mistake false statements as true, rather than the reverse, even in the absence of cognitive load and even when the statements are explicitly tagged as false (Pantazi, Kissine, & Klein, 2018). According to these researchers, this implies that truth bias is not the product of automatic belief (Pantazi et al., 2018).

Finally, some researchers claim that variability in truth bias counts against the idea that belief is the immutable default of comprehension, countering the provocative Spinozan claim that "You can't not believe everything you read" (Gilbert et al., 1993). Truth bias appears to be moderated by context (Dechêne et al., 2010), source credibility (Nadarevic & Erdfelder, 2013; Henkel & Mattson, 2011), the degree to which the statements are informative (Hasson, Simmons, & Todorov, 2005; Fillenbaum, 1966), and background knowledge or beliefs (Richter, Schroeder, & Wöhrmann, 2009; but see Fazio, Brashier, Payne, & Marsh, 2015). Consistent with the Cartesian view, these findings suggest that believing is not always the default. Rather, Cartesian belief theorists argue that there is an efficient evaluation process that sets the default based on background knowledge, context, and so forth.

If truth bias is not the result of automatic belief, what explains it? The most common, non-Spinozan explanation for truth bias appeals to processing fluency, that is, ease of comprehension. Under this view, repetition makes statements easier to process, which leads individuals to conclude that such statements are more likely to be true, even when they are known to be false (Unkelbach & Stahl, 2009; Unkelbach, 2007). Consistent with this view, some studies have reported illusory truth effects as a result of fluency, even in the absence of prior exposure: Statements written in easy-to-read fonts are more often rated as true (Unkelbach, 2007; Reber & Schwarz, 1999).

Confidence, Probability, and Reward Anticipation

Considerable prior research has investigated the neural bases of confidence (e.g., Kiani & Shadlen, 2009; Kepecs, Uchida, Zariwala, & Mainen, 2008; Aron et al., 2007; Hampton & O'Doherty, 2007; Knutson, Rick, Wimmer, Prelec, & Loewenstein, 2007; Heekeren, Marrett, Bandettini, & Ungerleider, 2004; Glimcher, 2003; Shadlen & Newsome, 1996, 2001), uncertainty (Platt & Huettel, 2008; Glimcher, 2003), and representations of probabilities (see Ma & Jazayeri, 2014 and Meyniel, Sigman, & Mainen, 2015, for comprehensive reviews). However, this work has focused on identifying the neural architecture responsible for tracking and contrasting degrees of confidence and the representations of varying probabilities (e.g., high vs. low). Here, however, we are not contrasting high versus low degrees of belief, but rather contrasting belief as a mental state with different mental states. More specifically, we are asking how believing that the world is a certain way differs from (a) wanting the world to be that way and (b) merely thinking about the world as being that way.

Likewise, many studies have examined degrees of desire in different forms. Most often, desire has been conceptualized in the literature as predictive value tracking or stimulus valuation (e.g., Chib, Rangel, Shimojo, & O'Doherty, 2009; Hare, O'Doherty, Camerer, Schultz, & Rangel, 2008; Kable & Glimcher, 2007; Plassmann, O'Doherty, & Rangel, 2007; Tom, Fox, Trepel, & Poldrack, 2007; Sugrue, Corrado, & Newsome, 2005), as reward uncertainty, (e.g., O'Neill & Schultz, 2010; Yacubian et al., 2007; Abler, Walter, Erk, Kammerer, & Spitzer, 2006; Dreher, Kohn, & Berman, 2006; Fiorillo, Tobler, & Schultz, 2003; Critchley et al., 2001), or as reward anticipation (see Knutson & Greer, 2008, for a meta-analysis). However, this prior work has focused primarily on neural responses to variability in reward amount or likelihood. In the present research, we are not contrasting high levels of desire with low levels—or even no desire at all. Rather, we are contrasting desiring that the world be a certain way with believing that it is that way or merely thinking about it is being that way.

In short, many studies have examined the neural mechanisms associated with encoding degrees of belief or degrees of desire, but they have not contrasted these propositional attitudes with each other while controlling for the propositional content of the belief/desire. Nor have they contrasted belief or desire with mere thought, where the propositional content remains the same, but both belief and desire are absent. In the present work, we do just that, focusing on the differences between the neural instantiation of distinct propositional attitudes, rather than variation within the attitudes of belief or desire.

The Present Research

The present research examines the neural mechanisms of believing and withholding belief, testing predictions made by the Spinozan and Cartesian theories. We use fMRI coupled with our shell game task, which systematically induces participants to form beliefs, desires, or mere thoughts about the location of a hidden target object. As noted above, this strategy has several advantages over prior research. First, and most important, this strategy provides experimental control over what is believed, desired, or merely thought about. Once again, this enables us to dissociate propositional attitudes from propositional content. Second, our task does not require participants to report on their beliefs or desires, minimizing confounds related to metacognitive processing. Third, participants do not have direct perceptual experience of the propositions in question (i.e., seeing the target object in the target location). This distinguishes the present research from the vast body of research on perception and memory and allows us to focus specifically on the mechanisms of believing and withholding belief.

We directly test the Spinozan theory by searching for neural responses consistent with "unbelieving," the active withholding of belief. This inhibitory account contrasts with an alternative Spinozan account whereby unbelieving is executed by "tagging" beliefs as not true, whereas representing a belief as true requires no special tag. Although both inhibition and "tagging" could result in non-belief, they are different in much the way that censorship differs from applying a warning label. The former involves the prevention of a process, whereas the latter involves the appending of information. Evidence for the belief inhibition version of the Spinozan account would entail the engagement of inhibitory control processes dependent on the prefrontal cortex (Munakata et al., 2011; Dias, Robbins, & Roberts, 1997) when participants represent a proposition without believing that it is true. We also test a version of the Cartesian theory of belief by searching for activation that is specific to believing. (The Cartesian theory does not necessarily entail the activation of a specific *process* for belief, although the distinction between believed and non-believed propositions must be encoded somehow.)

As suggested above, a strong version of the Spinozan theory predicts that "unbelieving" processes will be engaged under two different conditions of non-belief: (1) when participants think about a proposition while neither believing that it is true nor desiring that it be true, and (2) when participants desire that a proposition be true without believing that it is true. If both predictions are confirmed, this would provide evidence that "wishful thinking" is a special case of truth bias, resulting from a failure of Spinozan belief inhibition.

METHODS

Participants

Eighty-seven people (47 women; ages 18–64 years) participated in this study. All were native English speakers, right-handed, and had no history of neurological conditions. Of these, 8 were excluded for poor performance (less than 70% accuracy) on the attention check task (see details below). Eight other participants were excluded for excessive motion during scanning, which was defined as 2 *SD*s from the group mean on two of the three following motion parameters: average absolute motion per run, average number of movements greater than 0.5 mm per run, and average per run slice-wise signal-to-noise ratio. Finally, one participant was excluded because of technical issues leading to incomplete data. The remaining 70 participants were included in all subsequent analyses described throughout the article.

Data were collected in two batches. After scanning the first 30 usable participants, the data were analyzed. We then resumed scanning until we had collected data from an additional 40 participants who met our inclusion criteria. This target sample size of 70 usable participants was determined after the collection and analysis of the data from the first 30 participants and was preregistered (Open Science Framework [https://osf.io/gs82p/]). The sample size (n = 30) for the original, exploratory sample was not based on a power analysis, as we had no reliable indications about likely effect sizes. However, the second sample size (n = 40) was based on a power analysis for a test of object classification accuracies in the left parahippocampal gyrus using multivariate pattern analysis. This sample was chosen to obtain 90% power to detect an effect (average classification accuracy across participants) of the size that we originally observed in our first sample.

Although our power analyses were not conducted with the combined 70-participant sample in mind, the larger sample, along with our use of simpler univariate methods, makes the analyses reported here better powered than the analyses targeted in our power analysis for the second sample. Our preregistered analysis plan included provisions for both a two-study exploratory/confirmatory analysis structure and an analysis of the full 70-participant data set. The former yielded suggestive findings, but key results did not survive stringent whole-brain correction within either subset. Nor did they survive an ROI-based analysis of the second subset. Here, we report on our preregistered analyses (with whole-brain correction) using the full set of 70 participants.

Stimuli

We developed a novel dynamic visual paradigm modeled after the classic street-side shell game (see Figure 1). The shell game task allows us to freely and arbitrarily manipulate the propositional attitudes (i.e., believing, desiring, or mere thinking) that participants have about different propositions (i.e., different positions of concealed objects). Participants view images of four objects (a dog, a mop, a snake, and a hose). After 5 sec, blue squares cover each object and a verbal cue indicates which object is the "target" on that trial, as well as which type of trial it is going to be ("track," "bonus," or "think"; described below). Then, the concealed objects are shuffled and distributed to each of the four corners of the screen.

Trials have three types: "track," "bonus," and "think," which induce belief, desire, and mere thinking, respectively. On track trials, participants track the location of the concealed target object. On these trials, the objects are shuffled in such a way that the (concealed) target object is easy to follow, and its final location is clear to the participant. Thus, during a track trial, participants have a *belief* about the target object's final location. However,

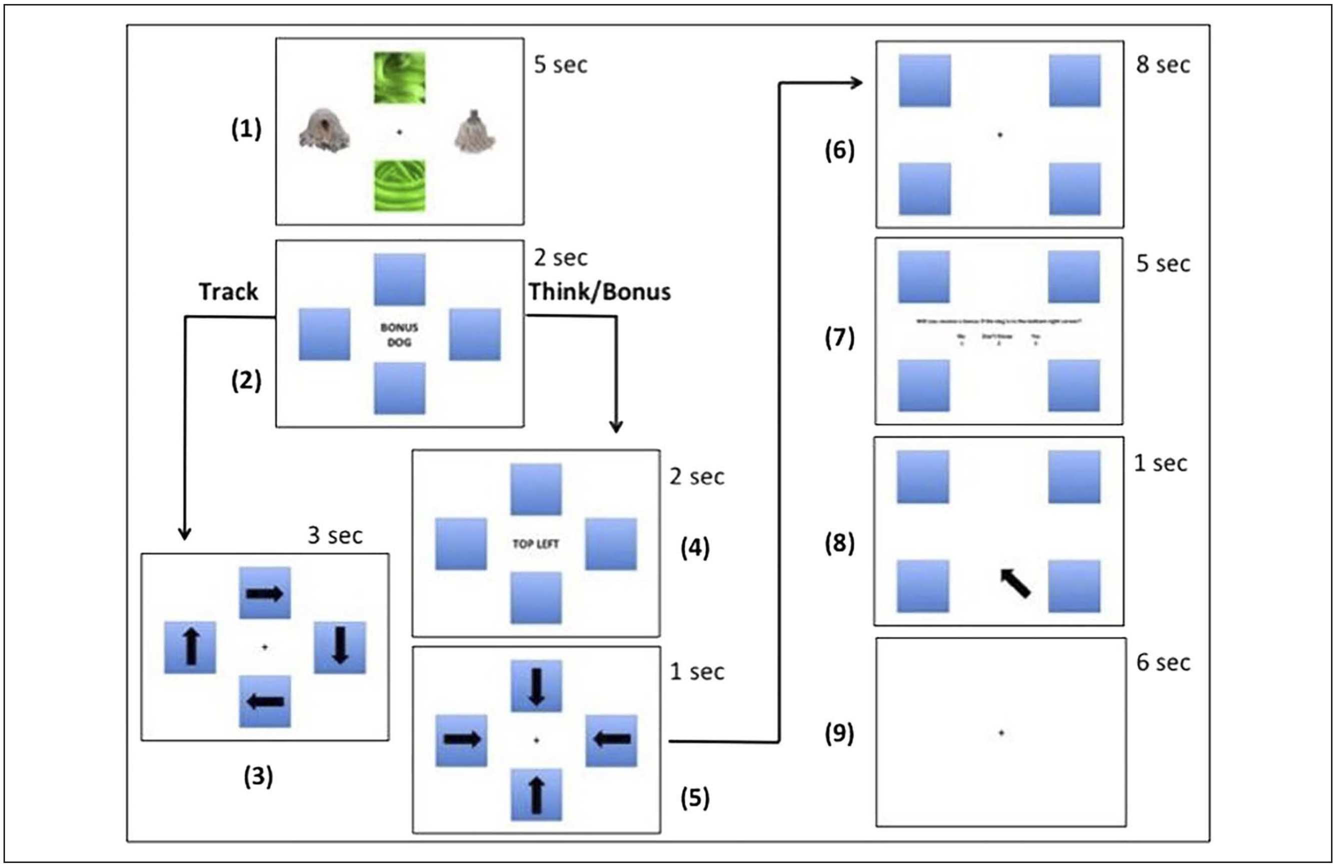


Figure 1. Task sequence and timing. (1) The objects are randomly placed in one of four locations (left, right, top, and bottom) for 5 sec. During this time, participants must learn the starting location of each object. (2) The objects are covered (for 2 sec), and participants learn the trial type (track, think, or bonus) and which of the four objects is the target object. (3) In track trials (belief condition), the blue squares are then shuffled. Over the course of 3 sec, the blue squares are either moved to their final locations or participants' view arrows pointing to the squares' final locations. (4) In the think trials (mere thought condition) and bonus trials (desire condition), a screen displays the target location for 2 sec. (5) The blue squares are then shuffled over the course of 1 sec either by having the squares move around the screen or by having arrows point to the squares' next location. Importantly, the objects in the think and desire/bonus trials are impossible to track, giving participants no knowledge of their final locations. (6) In all three trial types, the shuffle is followed by an 8-sec delay period. It is during this time period that all of our critical analyses are performed. (7) The delay period is followed by the attention check question, which participants have 5 sec to answer. (8) An arrow is then displayed on the screen for 1 sec, showing the final location of the target object. (9) Each trial ends with a 6-sec intertrial interval.

critically, they are given no special reason to desire that it be there. Accordingly, these trials constitute our "belief" condition. On "bonus" trials, participants are verbally informed about a target location in addition to a target object. Participants receive a $5 bonus if the target object ends up in the target location on a bonus trial. As they watch, the objects are shuffled in such a way that it is impossible to track the target object. Thus, participants desire that the target object be in the target location, but they are given no (good) reason to believe that the target object is in that location rather than any other. These trials constitute our "desire" condition. Finally, "think" trials closely resemble bonus trials in structure and visual content. After being informed about the trial type and the target object, participants are given a target location and are told to merely think about the target object as being in the target location. Critically, in the think condition, participants do not receive a bonus if the target object ends up in the target location, or anywhere else. Consequently, participants in the think condition have little reason to believe that the target object is in the target location; nor do they have reason to desire that the target object be in the target location.

To confirm that we successfully manipulated the degree to which participants had beliefs and desires in the relevant conditions, we asked our first 30 participants to complete a follow-up survey designed to evaluate the degree to which they believed and desired the target outcome in each condition. Specifically, to measure how strongly they believed that the target object was in the target location, we asked participants, "When you [had to track the target object to/had to think about the target object being in/got a bonus if the target object went to] the target location, how strongly did you believe it was there?" Participants responded on a 1–5 scale anchored at *not very much* and *very much*. Consistent with our expectation that participants held a stronger belief about the location of the target object in the track trials than in the bonus or think trials, we found that responses were significantly higher for the track trials ($M = 4.59, SD = 0.68$) than in the bonus ($M = 2.72$, $SD = 1.25$; $t(28) = 6.37$, $p < .0001$) or think trials ($M = 2.21, SD = .94$; $t(28) = 11.84, p < .0001$). However, in both desire and think trials, participants' average responses fell at the midpoint of the scale, suggesting that they were not operating with a complete absence of belief in these conditions. Nevertheless, these data indicate that the belief condition produces beliefs about the object's location far more than the desire and think conditions.

This survey also included a measure of how strongly participants desired that the target object be in the target location. Specifically, we asked the first set of participants (n = 30), "On a [Bonus/Think/Track] trial, how much would you have paid to have the target object end up in the target location?" Participants responded on a $0–2.00 scale in $0.50 increments (scale values ranging from 1–5). On average, participants were willing to pay $1.54 (out of $2.00) to have the desired outcome in bonus trials, but only $0.47 to have the desired outcome in think trials and $0.58 for the desired outcome in track trials. Paired-samples t tests confirmed that participants were willing to pay significantly more for the desired outcome in bonus than think trials, $t(28) = 10.61, p < .0001$, and in bonus than track trials, $t(28) = 6.98, p < .0001$. Moreover, one-sample t tests confirmed that participants' responses in think and track trials were not significantly different from $0 (think: $t(28) = 1.98, p = .057$; track: $t(28) = 1.94, p = .062$), but was for bonus trials, $t(28) = 12.37, p < .0001$. Given these results, we felt confident that participants were experiencing meaningful differences in their levels of belief and desire between conditions.

Because the shuffles in belief trials are always trackable, whereas shuffles in the desire and think trials are not, shuffle trackability is confounded with attitude type. The shuffles occur before the extended delay period on which our main analyses are based. To ensure that incidental perceptual differences in shuffle type during the prior period are not responsible for effects observed during the critical delay period, we generated two different shuffle styles. In one, the concealed objects visibly rotate around the screen. In the other, arrows appear on the screen indicating the final location of each of the concealed objects (in track/belief trials), or pointing to the center of the screen (in bonus/desire and think trials). The concealed objects then disappear from and reappear in each of the four corners of the screen. Creating two shuffle styles allows us to perform follow-up analyses assessing whether features of the shuffle are responsible for effects observed during the delay period. Our main analyses, however, were performed collapsing across shuffle styles. We note that differences observed between the think and desire conditions cannot be explained by differences in shuffle style because these two conditions both employ the same, nontrackable shuffle.

After the objects are shuffled, participants view a delay screen for 8 sec with the four blue squares in each corner and a fixation cross in the center. All analyses were performed using the modeled hemodynamic response corresponding to this delay period only. During this time, participants view the same screen (four blue squares, one in each corner) in all three conditions. Thus, during the delay period, the perceivable stimuli are identical, eliminating potential perceptual confounds.

The delay screen is followed by an attention-check, which ensures that participants have encoded the relevant information on each trial. Specifically, participants read one of the following questions:

Is the [target object] in [specific location]?
Will you get a bonus if the [target object] is in [specific location]?
Were you asked to think about the [target object] being in [specific location]?

Participants respond using a 1–3 scale (1 = *No*, 2 = *Don't Know*, 3 = *Yes*) by pressing the corresponding button on a button box held in their right hands. These questions are randomly assigned to each trial so that participants only receive the question specifically probing the mental state (believing, desiring, or thinking about) induced by the current trial type on approximately 1/3 of the trials. This was done to avoid confounding the condition with the expectation of a specific question. Furthermore, although we always ask about the target object, we ask about the target location on only 50% of the trials. On the remaining trials, we ask about a random, non-target location. In this way, participants are required on all trials to attend to and remember the trial type, the target object, and the target location. Responses were coded as correct depending on the question, condition, and location that was asked about as described above (see Table 1).

Finally, an arrow is flashed on the screen showing the final location of the target object. This arrow is randomly placed in one of five locations on the screen to eliminate any effect of anticipating the arrow's location. In belief/track trials, the arrow tells participants whether they correctly tracked the object. In desire/bonus trials, it tells participants whether they will receive a bonus on that trial. In the think trials, the arrow merely informs the participant of the target object's final location.

Importantly, participants never see any of the objects in their final locations. The objects begin each trial centered near each edge of the screen but are covered before they are moved to their final locations in the four corners. Critically, this feature of our paradigm enables us to examine neural activity associated with beliefs, desires, or thoughts about hidden states that have not been directly perceived and that therefore cannot be remembered.

Experimental Procedure

The task consists of 12 runs of 12 trials each. Each target object and condition (belief, desire, or think) was pseudorandomly assigned on each trial, such that each object was the target object 3 times per run and each condition occurred 4 times per run. The order of presentation was randomized across trials within each run. The target location for each trial was also pseudorandomly assigned such that the target location was randomly assigned on each trial, but target locations were equalized over the entire experiment (random without replacement). Participants received a bonus in only 25% of the desire trials (12 out of 48) to minimize their ability to anticipate the final location of the target object in these trials. These 12 trials were randomly distributed throughout the experiment. A single trial took 30 sec, with a minimum 30-sec break between runs. The duration of the entire experiment was approximately 80 min.

fMRI Acquisition and Preprocessing

Neuroimaging was performed using a Siemens Prisma 3.0 T scanner with a 32-channel head coil at the Harvard Brain Sciences Center in Cambridge, MA. A high-resolution structural scan was performed before functional data acquisition using a 3-D magnetization prepared rapid gradient echo sequence (repetition time [TR] = 2530 msec,

Table 1. Participants Were Asked One Attention Check Question at the End of Each Trial

Question	*Condition*	*Location Specified in Question*	*Responses Accepted as Correct*
Is the [target object] in [specific location]?	Belief	Target location	Yes
		Non-target location	No
	Desire or think	Target location	Don't know
		Non-target location	Don't know
Will you get a bonus if the [target object] is in [specific location]?	Desire	Target location	Yes
		Non-target location	No
	Belief or think	Target location	No
		Non-target location	No
Were you asked to think about the [target object] being in [specific location]?	Think	Target location	Yes
		Non-target location	No
	Belief or desire	Target location	Yes or no
		Non-target location	No

These questions were randomly assigned to the trial. Although the questions always asked about the target object, 50% of the questions asked about a non-target location. Correct answers depended on the combination of question, condition, and specified location.

echo time = 1.69 msec, flip angle = 7°, field of view = 256 mm, slice thickness = 1.0 mm, 176 slices). The EPI pulse sequence for functional scans used a 2000 msec TR with 190TRs per functional run (echo time = 35 msec, flip angle = 80°, field of view = 207 mm, slice thickness = 2.2 mm, 69 slices). Stimuli were presented using the Psychtoolbox package for MATLAB (The MathWorks).

Data preprocessing was performed using an adaptation of AFNI's *afni_proc.py* program (https://afni.nimh.nih.gov/pub/dist/doc/program_help/afni_proc.py.html). The first five TRs were removed from each run. After performing despiking and slice time correction, each participant's EPI images were spatially registered to the first volume of the second run using cubic polynomial interpolation. Data were smoothed for the univariate analyses with a Gaussian kernel at 6.6-mm FWHM (the equivalent of three voxels). A mask was created to remove any voxels with more than 12 TRs with no data and was used for all subsequent single-subject analyses.

Univariate Analyses

The hemodynamic response function deconvolution for the BOLD signal corresponding to the critical delay period was performed using AFNI's *3dDeconvolve* with a BLOCK model set for an 8-sec event duration (length of the delay period on each trial). An ordinary least squares regression was performed, with condition (i.e., belief, desire, or think) as the primary regressors, and motion parameters entered as regressors of no interest. General linear tests on the contrasts of interest (belief vs. desire, belief vs. think, desire vs. think) were included in this analysis. Finally, the resultant individual participant whole-brain beta-maps were warped to Talairach (TLRC) space via a diffeomorphic nonlinear transformation using Advanced Normalization Tools (ANTs) (Avants, Tustison, & Song, 2009).

Group analysis was performed using one-sample *t* tests (with AFNI's *3dttest++* function) to identify clusters of voxels in which the average betas from the individual-participant general linear tests were significantly different from zero. Using the *Clustsim* flag in *3dttest++*, we ran the Monte Carlo simulation to perform cluster-wise correction for multiple comparisons on the resultant *t* maps. As specified in our preregistration, a threshold for statistical significance was set at a voxel-wise $p < .001$, and a cluster-wise corrected threshold of $p < .05$. To identify brain regions preferentially activated by the belief condition, we ran separate *t* tests for the belief versus desire contrasts and belief versus think contrasts. We then looked for clusters of overlap between significant voxels from both tests. To identify those brain regions preferentially activated by the desire condition, we ran separate *t* tests for the desire versus belief contrasts and desire versus think contrasts. We then looked for clusters of overlap between significant voxels from both tests. Finally, to identify neural activation associated with "unbelieving" (thinking about a proposition without belief), we looked for clusters of overlap between significant voxels for the desire versus belief, and think versus belief contrasts.

Multivariate Analyses

Our multivariate analyses had two objectives. The first was to identify regions that encoded the identity of the target objects or target locations across the attitude condition. To this end, at the participant level, a single image for each trial was created by averaging over the temporal interval from 6 to 14 sec after the start of the critical 8-sec delay period. Using this data, we ran searchlight analyses (Kriegeskorte & Bandettini, 2007) implemented with the Searchmight Toolbox (Pereira & Botvinick, 2011). A cube with a 2-voxel (6.6 mm) radius was centered at each voxel, and MATLAB's built-in Gaussian naive Bayes classifier (implemented with the *NaiveBayes.fit* function) was trained in each searchlight neighborhood to classify either the target object (mop, dog, snake, or hose) or target location (top–left, top–right, bottom–left, bottom–right) on each trial. Because we were interested in location or object representation across condition (belief, desire, and think), we trained our pattern classifier to identify which of the four locations or objects was presented in each trial for two of the three conditions and then tested the classifier's performance in trials from the third condition, cross-validating across each possible permutation of training and test conditions. This allowed us to ensure that no single condition was driving the classifier's success. This strategy produced three separate object classification accuracy maps and three location classification accuracy maps for each participant. These classification maps were then corrected by subtracting chance accuracy (0.25) from each value so that resultant values reflected accuracy above chance. Because we were ultimately looking for regions of overlap between these separate classifications, the individual participant above-chance accuracy maps were smoothed by applying a 4.4 mm (2 voxel) Gaussian blur using AFNI's *3dMerge*. The smoothed accuracy maps were then warped to TLRC space using ANTs. Next, we ran one-sample *t* tests with AFNI's *3dttest++* to identify clusters of voxels where classification accuracy was significantly above chance across participants. Finally, we used the Monte Carlo simulation to perform cluster-wise corrections for multiple comparisons on the resulting *t* maps by running the *Clustsim* flag in *3dttest++*.

The second objective of our multivariate analyses was to identify distinct brain regions in which we could reliably decode the target object or target location within different attitude conditions. Although the brain must somehow distinguish believed propositions from non-believed propositions, the existence of attitude-specific object representations fits naturally with the Cartesian theory, according to which belief is a further process beyond comprehension. According to the Cartesian theory, a region might encode the identity of a hidden object as a dog, but only (or especially) when there is an active belief about the dog.

Likewise, regions might preferentially encode the identities of objects of desire or mere thought. We tested these hypotheses by searching for brain regions whose representational properties vary with propositional attitude.

To identify brain regions that preferentially encode object or location information only when participants are holding beliefs, desires, or merely thinking about the object or location, we used multivoxel pattern analysis to classify the target object or location on each trial within each condition. As with the previous analyses, the preprocessed BOLD signal for the 6–14 sec after the start of the critical 8-sec delay period was average to produce a single image for each trial. The data were then divided by condition, yielding 48 trials per condition, per participant. Using a whole-brain searchlight analysis and a leave-one-run-out cross-validation procedure, we trained our classifier to identify which of the four objects or which of the four locations was presented in each trial for 11 of 12 runs and then tested the classifier's performance in the 12th run, repeating this process for every permutation of training and test runs and averaging the classification accuracies across permutations. These analyses provided us with one set of whole-brain maps of the object classifier's accuracy for each condition for each participant, and a second similar set of maps for location classification accuracy. To assess differences in object or location representation between conditions, for each participant, we subtracted the voxel-wise accuracies for one condition from the voxel-wise accuracies for a second attitude condition (e.g., object classification accuracy in belief trials minus object classification accuracy in think trials). Both the within-condition accuracy maps and the maps of difference scores were warped to TLRC space using ANTs. Group-level significance testing was performed with one-sample *t* tests using AFNI's *3dttest++*, with whole-brain correction for multiple comparisons implemented using the *Clustsim* flag.

RESULTS

Behavioral Results

As expected, condition (belief vs. desire vs. think) had little effect on participants' responses to the attention check questions. To test the effect of question and condition on accuracy, for each participant, we computed an average accuracy for each question within each condition (e.g., "Is the [target object] in the [specific location]?" for belief trials, for desire trials, and for think trials separately). Across participants, the average accuracy for each question type within each condition was high, with a minimum average accuracy of 89.91% correct and a maximum average accuracy of 96.66% correct. We note that the correct response for some attention-check questions is "I don't know" (e.g., asking about the target object's location in "think" or "desire" trials). We then performed a mixed effect linear regression, implemented with the *lmer* function from the *lme4* package in R (Bates, Mächler, Bolker, & Walker, 2015) to evaluate the degree to which question, condition, and their interaction predicted average response accuracy. This model also included a random intercept for each participant. We then compared this model to reduced models that excluded condition, question, or their interaction separately using the *ANOVA* function in R. We found that the full model performed significantly better than the model excluding the interaction term, $X^2(4, n = 70) = 16.85, p < .005$. This effect is likely driven by slightly reduced performance in response to the "Is the [target object] in the [location]?" question on belief trials (see Figure 2). It is worth noting, though, that accuracy in this case is still very high ($M = 89.92\%, SD = 0.13$). Critically, although there was some variation in accuracy across specific questions in specific conditions, accuracy was high for all questions in all conditions. Thus, our behavioral analyses confirmed that participants were consistently encoding the relevant information in all three conditions.

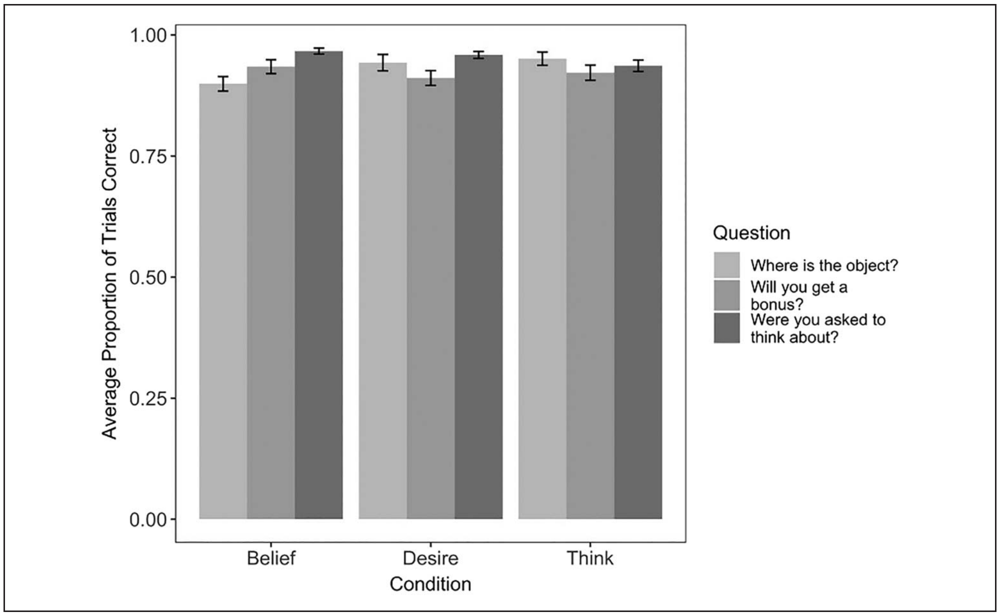


Figure 2. Behavioral results averaged across participants. After each trial, participants were asked one of three questions ("Is the [target object] in the [location]?", "Will you get a bonus if the [target object is in the [specific location]?", "Were you asked to think about the [target object] being in the [specific location]?"). One question was randomly selected for each trial. Participants were therefore asked each question in each of the three conditions.

Unbelieving

To directly test the Spinozan theory, we searched for regions exhibiting increased activity on trials when participants did not form a belief concerning the target object's location. That is, we focused on the contrasts *think* > *belief* and *desire* > *belief*. The *desire* > *belief* contrast yielded effects in 10 clusters exceeding the preregistered voxel-wise and cluster-wise corrected thresholds for significance. These include clusters in bilateral superior frontal gyrus, left supramarginal gyrus, middle temporal gyrus, and middle frontal gyrus (see Table 2). For the contrast *think* > *belief*, we observed effects in the right IFG and right insula at the prespecified voxel-wise threshold of $p < .001$. At this voxel-wise threshold, these clusters approach corrected significance at $p = .08$ and $p = .09$, respectively (two-tailed; see Table 1). We identified one 61 voxel cluster of overlap between these two contrasts (*desire* > *belief* and *think* > *belief*) in the right IFG (see Figure 3).

To further interrogate these overlapping results in the IFG, we reran these contrasts at a more stringent voxel-wise threshold of $p < .0005$. Using this higher voxel-wise threshold, both contrasts produced clusters in the right IFG that survive whole-brain correction for multiple comparisons at a cluster-wise corrected threshold of $p < .05$. We find a 35-voxel cluster overlap between the results of these two contrasts in the right IFG.

Believing

To directly test the Cartesian theory (which posits the engagement of a distinct belief process), we searched for regions exhibiting increased activity on trials when participants did form a belief concerning the target object's location. That is, we focused on the contrasts: *belief* > *desire* and *belief* > *think*. The *belief* > *desire* contrast yielded significant effects in the right precuneus,

Table 2. Univariate Activation Associated with *Non-belief*

		TLRC Coordinates[b]				
L/R	*Anatomical Region*[a]	*x*	*y*	*z*	*Peak z Score*	*Cluster Size (Voxels)*
Desire > *belief*						
L/R	Superior frontal gyrus	−11.5	42.5	32.5	6.83	10301***
L	Supramarginal gyrus	−47.5	−59.5	30.5	7.64	1776**
L	Middle temporal gyrus	−55.5	−31.5	−1.5	6.02	1565**
L	Middle frontal gyrus	−37.5	10.5	48.5	6.61	1020**
R	Middle temporal gyrus	56.5	−27.5	−9.5	5.41	735*
R	Supramarginal gyrus	48.5	−55.5	30.5	6.41	692*
L	IFG	−49.5	16.5	14.5	4.86	464*
L/R	Cingulate gyrus	−7.5	−19.5	30.5	5.45	396*
R	Pyramis	32.5	−73.5	33.5	5.14	377*
R	Middle frontal gyrus	40.5	−10.5	44.5	4.92	306*
Think > *belief*						
R	IFG	44.5	32.5	8.5	4.60	158[c]
R	Insula	40.5	4.5	14.5	4.25	369[c]
Overlap						
R	IFG	45.1	32.2	5.4	n/a	61

All clusters surpass a voxel-wise significance threshold of $p < .001$.

[a] Indicates anatomical region containing largest proportions of voxels, although in some cases cluster extends through additional regions.

[b] TLRC coordinates for voxels of peak activation for entire cluster. For overlap, it indicates coordinates in the approximate center of the cluster.

[c] Cluster-wise corrected $p < .10$.

* Cluster-wise corrected $p < .05$.

** Cluster-wise corrected $p < .01$.

*** Cluster-wise corrected $p < .005$.

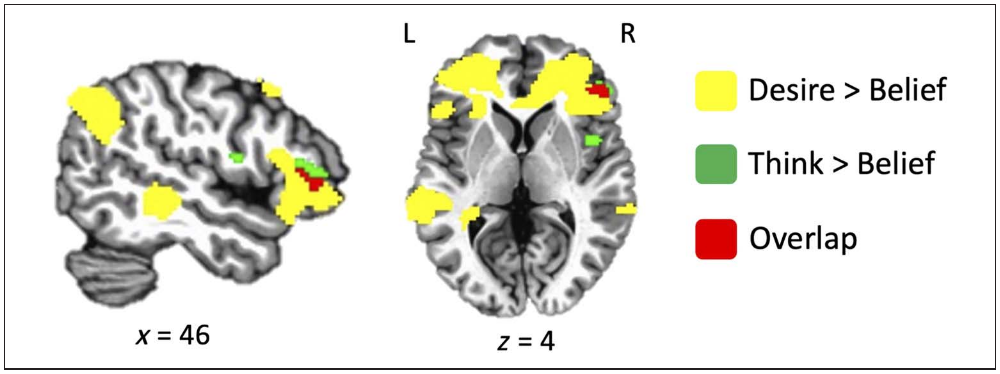


Figure 3. Greater neural activation associated with non-belief conditions relative to the belief condition in the right IFG. Desire > belief contrast: voxel-wise $p < .001$, cluster-wise corrected $p < .05$. Think > belief contrast: voxel-wise $p < .001$, cluster-wise corrected $p < .10$ (two-tailed). Coordinates are in TLRC space.

parahippocampal gyrus, middle occipital gyrus, and insula (voxel-wise $p < .001$, cluster-wise corrected $p < .05$). The *belief > think* contrast yielded significant effects in eight clusters including in the bilateral precuneus, bilateral middle frontal gyrus, and right thalamus (voxel-wise $p < .001$; cluster-wise corrected $p < .05$; see Table 3). We identified two clusters of overlap between these two contrasts (*belief > desire* and *belief > think*): a large cluster primarily in the right precuneus and a smaller cluster in the left cuneus (see Figure 4).

Table 3. Univariate Activation Associated with *Belief*

		TLRC Coordinates[b]				
L/R	*Anatomical Region*[a]	*x*	*y*	*z*	*Peak z Score*	*Cluster Size (Voxels)*
Belief > desire						
R	Precuneus	34.5	−81.5	26.5	7.09	11654***
R	Parahippocampal gyrus	40.5	−13.5	−23.5	5.68	1268**
L	Middle occipital gyrus	−33.5	−81.5	24.5	7.13	1237**
R	Insula	40.5	−9.5	−5.5	4.77	273*
Belief > think						
L/R	Precuneus	10.5	−73.5	52.5	6.74	6571***
R	Middle frontal gyrus	22.5	−5.5	48.5	5.58	1159**
L	Middle frontal gyrus	−19.5	−5.5	54.5	4.69	538*
R	Thalamus	16.5	−25.5	12.5	4.59	351*
L	Cerebellar tonsil	−15.5	−37.5	37.5	5.37	303*
R	Middle frontal gyrus	40.5	58.5	6.5	4.87	289*
L	Cerebellar tonsil	−41.5	−61.5	−37.5	4.63	288*
L	Cuneus	−27.5	−83.5	28.5	5.02	254*
Overlap						
R	Precuneus	19.0	−64.2	46.3	n/a	3542
L	Cuneus	−29.0	−82.0	27.9	n/a	188

All clusters surpass a voxel-wise significance threshold of $p < .001$.

[a] Indicates anatomical region containing largest proportions of voxels, although in some cases clusters extend through additional regions.

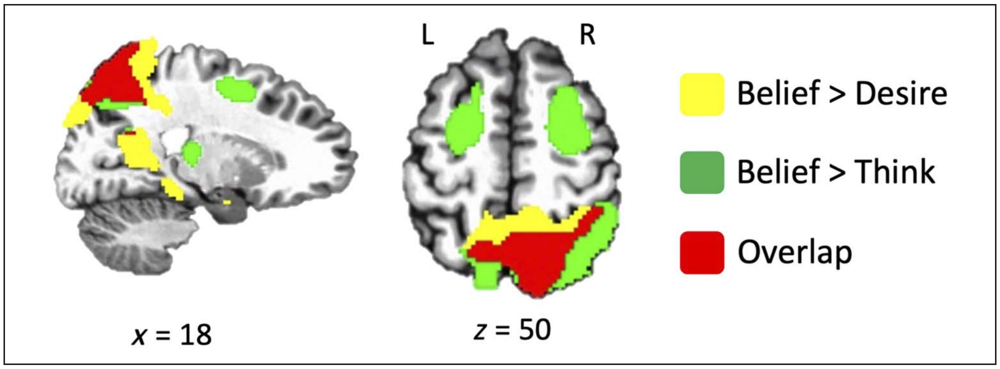
[b] TLRC coordinates for voxels of peak activation for entire cluster. For overlap, it indicates coordinates in the approximate center of the cluster.

* Cluster-wise corrected $p < .05$.

** Cluster-wise corrected $p < .01$.

*** Cluster-wise corrected $p < .005$.

Figure 4. Greater neural activation associated with the belief condition relative to the desire and think conditions in the right precuneus and left cuneus. Voxel-wise $p < .001$, cluster-wise corrected $p < .05$. Coordinates are in TLRC space.



Because *belief* trials also involved object tracking, whereas *desire* and *think* trials do not, we tested for a potential confound of object tracking by examining the neural activation within belief trials associated with each of our two shuffle types. Recall that the concealed objects were shuffled around the screen either by having the blue squares visibly rotate around the screen or by having arrows indicate the blue squares' final location. To test whether it is possible that the belief-specific activation identified in the previous analyses was related to object tracking, within each condition, we compared activation associated with each of the two shuffle types. Specifically, we used the same procedures for univariate analyses described above, but focused our analyses on the hemodynamic response corresponding to the 3-sec shuffle period. We then compared activation for trials that utilized the "rotation" shuffle to those that utilized the arrows shuffle. Across all three conditions, we found significantly increased activation for the rotation, when compared with the arrow shuffle, in the bilateral medial pFC (voxel-wise $p < .001$, cluster-wise $p < .05$; 2851 voxels; peak TLRC $x = -1.5$, $y = 26.5$, $z = -5.5$). Conversely, we found increased activation in the bilateral precuneus, inferior parietal lobule, and superior parietal lobe (voxel-wise $p < .001$, cluster-wise $p < .05$; 3790 voxels; peak TLRC $x = -23.5$, $y = -73.5$, $z = 44.5$) for the arrow shuffle when compared with the rotation. This cluster significantly overlaps with the cluster of voxels that were preferentially activated for *belief* rather than *desire* or *think* trials.

Desiring

To identify neural activity associated specifically with desiring, we performed the contrast *desire* > *think*, to complement the contrast *desire* > *belief* contrast performed above. The *desire* > *think* contrast yielded 12 clusters whose significance survived corrections for multiple comparisons (voxel-wise $p < .001$, cluster-wise corrected $p < .05$) including in the bilateral middle frontal gyrus, inferior parietal lobule, and middle temporal gyrus (see Table 4). Our overlap analysis revealed five distinct clusters of overlap, each greater than 100 voxels, in the posterior inferior parietal lobule, middle frontal gyrus, middle temporal gyrus, middle frontal gyrus, and dorsolateral pFC (see Figure 5).

Decoding Target Object/Location across Attitude Condition

As described above, to identify regions that reliably encode information about the target object or target location across conditions, we ran three separate whole-brain searchlight pattern-classification analyses—one with each condition held out as the test condition—seeking regions that support the decoding of the target object or target location regardless of which condition is withheld at test.

With the desire condition withheld at test, there was one cluster in which we were able to decode the identity of the target object above chance (voxel-wise $p < .005$, cluster-wise $p < .01$, 2686 voxels; centered at TLRC $x = 32.3$, $y = -1.7$, $z = 3.3$). This cluster was centered in the right caudate but included voxels in the right superior temporal gyrus, right lentiform nucleus, right insula, and right IFG. However, we were unable to decode the identity of the target object when either of the other two conditions were held out as the test condition.

Our three location classifications yielded a large region (13,102 voxels; centered at TLRC $x = 0.8$, $y = -76.4$, $z = 4.1$) encompassing most of the visual cortex in which we were able to decode the target location at significantly better than chance accuracy (voxel-wise $p < .005$, cluster-wise $p < .05$), regardless of which condition was held out as the test condition during classification.

Preferential Encoding of Object/Location within Attitude Condition

We were unable to decode the identity of the target object within condition at significantly better than chance accuracy. We were able to decode the identity of the target location above chance within each of the three conditions in the visual cortex (*belief*: 6965 voxels; peak TLRC $x = 2.5$, $y = -85.5$, $z = 4.5$; *desire*: 7496 voxels; peak TLRC $x = 8.5$, $y = -87.5$, $z = 6.5$; *think*: 6862 voxels; peak TLRC $x = 4.5$, $y = -75.5$, $z = 2.5$; for all three conditions voxel-wise $p < .005$, cluster-wise $p < .05$). However, we were unable to identify any clusters in which we were able to identify the target location significantly better in one condition when compared with either of the other two.

Table 4. Univariate Activation Associated with *Desire*

		TLRC Coordinates[b]				
L/R	*Anatomical Region*[a]	*x*	*y*	*z*	*Peak z Score*	*Cluster Size (Voxels)*
Desire > belief						
See Table 1						
Desire > think						
L	Middle frontal gyrus	−33.5	50.5	8.5	6.07	7221***
L	Inferior parietal lobule	−43.5	−55.5	30.5	7.50	2351***
R	Middle frontal gyrus	26.5	48.5	−2.5	6.22	1928***
R	Inferior parietal lobule	50.5	−57.5	44.5	6.35	1749**
R	Middle frontal gyrus	44.5	12.5	46.5	5.84	1632**
L	Middle temporal gyrus	−57.5	−29.5	−11.5	6.17	1191**
R	Pyramis	−7.5	−71.5	−25.5	5.39	1180**
R	Middle temporal gyrus	58.5	−29.5	−9.5	5.98	883*
L/R	Precuneus	−5.5	−69.5	34.5	5.40	759*
L	Cerebellar tonsil	−39.5	−57.5	−35.5	5.41	602*
L/R	Cingulate gyrus	−5.5	−23.5	30.5	4.59	372*
R	Caudate	8.5	8.5	8.5	5.78	350*
R	IFG	30.5	22.5	2.5	5.85	342*
Overlap						
L	Superior frontal gyrus	−7.7	36.5	32.1	n/a	3931
L	Inferior parietal lobule	−43.5	58	33.9	n/a	1526
R	Middle frontal gyrus	28.5	47.0	9.2		1219
L	Middle temporal gyrus	−55.6	−39.4	−5.0		1015
L	Middle frontal gyrus	−37.2	11.8	45.0		891
R	Supramarginal gyrus	47.3	−57.5	33.8		615
R	Middle temporal gyrus	58.1	−28.4	−7.4		584
R	Middle frontal gyrus	40.7	11.7	42.6		308
R	IFG	34.9	22.7	3.4		278
L/R	Cingulate	0.3	−23.8	30.3		241
L	IFG	−48.1	15.7	17.6		227
R	Pyramis	27.6	−68.3	−31.5		143

All clusters surpass a voxel-wise significance threshold of $p < .001$.

[a] Indicates anatomical region containing largest proportions of voxels, although in some cases cluster extends through additional regions.

[b] TLRC coordinates for voxels of peak activation for entire cluster. For overlap, it indicates coordinates in the approximate center of the cluster.

* Cluster-wise corrected $p < .05$.

** Cluster-wise corrected $p < .01$.

*** Cluster-wise corrected $p < .005$.

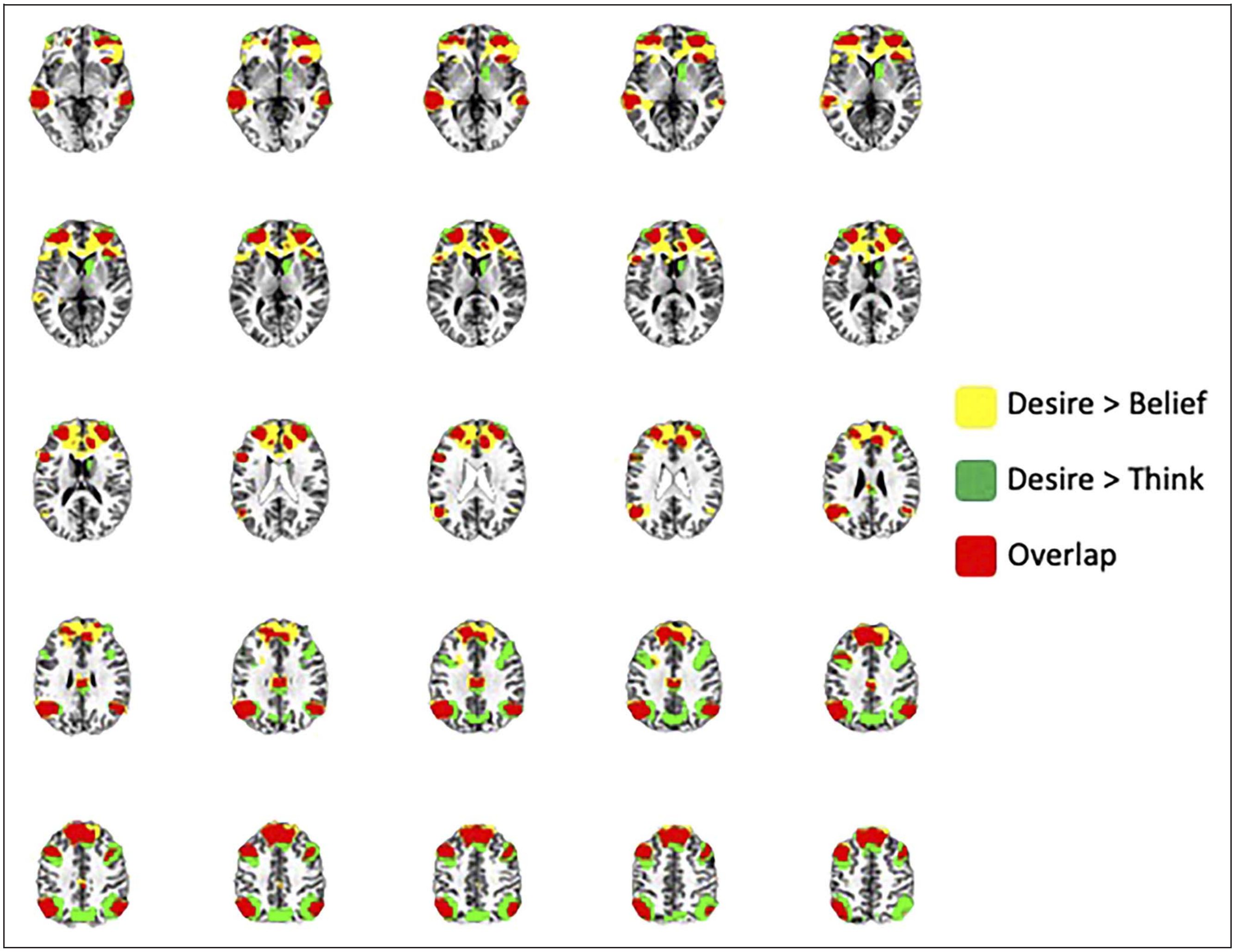


Figure 5. Greater neural activation associated with the desire condition relative to the belief and think conditions. Voxel-wise $p < .001$, cluster-wise corrected $p < .05$.

DISCUSSION

We provide evidence concerning a basic, unanswered question about the nature of belief: What distinguishes believing something from merely thinking about it? Prior behavioral research (Gilbert et al., 1990, 1993) has supported the Spinozan idea that thought without belief requires additional controlled processing. However, others have argued that these findings reflect uncertainty, rather than a process of unbelieving following a default tendency toward belief (Street & Kingstone, 2017; Street & Richardson, 2015). Neuroimaging studies have examined beliefs (Harris et al., 2008, 2009; Marques et al., 2009; Goel & Dolan, 2003), but they have not contrasted beliefs with other mental states with matched propositional/conceptual content. Nor have many of these studies distinguished metacognitive reporting on belief from belief itself. The large literature on confidence (degree of belief) in humans and animals is related to the present work (e.g., Platt & Huettel, 2008), but here, too, belief states are not contrasted with non-belief states matched for conceptual (or perceptual) content. Consequently, we have little empirical evidence concerning the cognitive and neural mechanisms that distinguish beliefs from other mental states with equivalent conceptual/propositional content. This is a significant gap in our understanding, as the capacity for entertaining complex ideas without believing in them appears to be an essential feature of high-level cognition, necessary for imagination, planning, and hypothesis testing in both science and everyday life.

Here, we deploy a new method, the shell game task, that enables us to experimentally induce states of belief, desire, and mere thought, while systematically controlling the propositional content of those mental states. Using this method, we have identified brain regions preferentially activated by believing, desiring, or merely thinking about ideas.

Most notably, we observed increased activity in the right IFG when participants represented an idea (or "proposition") without believing it. This was observed in both of the non-belief conditions (*think* > *belief* and *desire* >

belief). The increased activity in overlapping regions of the IFG for the two non-belief conditions provides evidence for the Spinozan theory of belief, which posits the existence of an additional process of "unbelieving" that is needed to entertain ideas without believing them. Moreover, these findings provide evidence for a specific version of the Spinozan theory whereby unbelieving is a process of inhibitory control supported by the IFG. This interpretation depends on a "reverse inference" (Poldrack, 2006), but one that is well supported by the literature.

Right IFG functioning is relatively heterogeneous. The region plays an important role in phonological and prosodic processing (Hartwigsen et al., 2010; Rota et al., 2009) and for the recovery of language function from stroke-induced aphasia (van Oers et al., 2010; Winhuisen et al., 2005). The right IFG has also been implicated in social cognition (Kilner, Neal, Weiskopf, Friston, & Frith, 2009), playing an important role in the experience of empathy (Shamay-Tsoory, Aharon-Peretz, & Perry, 2009), inferring unseen actions (Umilta et al., 2001), and theory of mind (Samson, Houthuys, & Humphreys, 2015; Samson, Apperly, & Humphreys, 2007).

However, this region has been most consistently implicated in response inhibition (see Aron, Robbins, & Poldrack, 2004, 2014, for reviews). The majority of the research on the right IFG and response inhibition has used the go/no-go and stop-signal tasks (see Swick, Ashley, & Turken, 2011, for a meta-analysis). In one such relevant study, the authors used a modified go/no-go task to differentiate between the cognitive inhibition, motor inhibition, and action cancellation components of motor inhibition tasks (Sebastian et al., 2013). Although engaging in inhibition in general increased activation in large portions of the right IFG, only the cognitive inhibition components of the task increased activation in the portion of the right IFG preferentially activated by non-belief trials in our study.

The right IFG has also been found to play a significant role in other types of psychological inhibition. It is preferentially engaged during some types of emotional inhibition including voluntarily suppressing negative affect (Phan et al., 2005), engaging in reappraisal to reduce emotional distress (Kim & Hamann, 2007; Ochsner et al., 2004), and mitigating emotional distractions (Dolcos & McCarthy, 2006). It has also been implicated in tasks requiring cognitive control, such as intentionally suppressing thoughts or memories as well as resolving stimulus conflict (Mitchell et al., 2007; Anderson & Green, 2001; Egner, 2011).

Finally, the IFG has been implicated specifically in withholding belief. Activation in the right IFG is increased when participants are required to withhold belief to evaluate the validity of logical syllogisms (Goel & Dolan, 2003), and disruption of the right IFG with TMS interferes with their ability to do so (Tsuji et al., 2010, 2011). Damage to the vmPFC also makes individuals increasingly susceptible to believing misleading advertising, even when they are told that the content of the advertisements is false (Asp et al., 2012). In light of such findings, Asp and Tranel (2013) have argued that the pFC is critical to Spinozan unbelieving, although they suggest that PFC serves to tag false beliefs rather than as engaging the inhibitory process we posit here.

The well-established importance of the right IFG in response inhibition, and the fact that our specific ROI has been implicated in several studies involving inhibition and cognitive control, suggests that it may also play an inhibitory role in our task. Importantly, the effects observed in our study create a double dissociation with a distinct set of brain regions that are more active for belief. Consequently, the effects associated with non-belief cannot be accounted for as products of increased overall attention or engagement. The desire and think conditions both involve the presentation of an additional verbal cue related to the target location, raising the possibility that the observed effects in the IFG reflect linguistic processing spilling over into the critical delay period. However, these effects are right-lateralized, the opposite of what one would predict on this alternative explanation. We also note that we observed no effects classically associated with reading (e.g., in the visual word form area) for the desire and think conditions during the critical delay period.

Other studies implicate the IFG in thought without belief. TMS to the left IFG has been shown to decrease susceptibility to the "good news/bad news" effect (Sharot et al., 2012), in which individuals more readily incorporate positive news into their beliefs but show an aversion to incorporating negative news. In this work, participants who received real TMS were more likely to believe bad news than those who received sham TMS. Finally, very recent research shows that the right IFG is preferentially engaged during the consideration or evaluation of counterfactual events (those that could have happened but did not), but not of events that actually occurred (Bernhard, Cushman, & Phillips, in prep; Nieuwland, 2012). In conjunction, this body of evidence, along with the current results, suggests a role for the IFG in inhibiting belief.

The increased activation in the IFG for desiring over believing is also consistent with an account of "wishful thinking" or "desirability bias" (Windschitl, Smith, Rose, & Krizan, 2010; Krizan & Windschitl, 2009) as a special case of Spinozan belief bias: Desiring a state of the world inherently involves thinking about that state of the world, which produces a belief in that state of the world unless it is inhibited by a process of unbelieving (Mandelbaum, 2014). This is consistent with decreased wishful thinking (Bamford & Lagattuta, 2020) and increased inhibitory control (Christ, White, Mandernach, & Keys, 2001) in children as they mature. We note, however, that desiring, relative to thinking, was associated with increased activity in a broad set of pFC regions, many of which are not specifically associated with inhibitory control. This suggests the need for further investigation specifically aimed at testing the hypothesis that wishful thinking results from a failure of unbelieving, understood as a failure of inhibitory control.

Although we interpret our findings in the right IFG as evidence of Spinozan inhibition, one might wonder whether our findings of increased activity for belief (relative to both desire and mere thought) in the cuneus and precuneus provide at least some support for the Cartesian theory, which posits that belief as a further process beyond comprehension. To the extent that this finding supports a Cartesian interpretation, it is a nonstandard Cartesian theory. The standard Cartesian theory posits a distinct process of truth-evaluation following comprehension, but it does not posit a distinct process that is specific to belief. Accepting our interpretation of our primary findings for the IFG, this would need to be a hybrid Spinozan–Cartesian theory whereby belief is a distinct process (Cartesian) that coexists with, and may be inhibited by, a Spinozan inhibitory process. Although this is an intriguing possibility, it depends on the assumption that the observed activity in the cuneus and precuneus do in fact reflect belief-specific processes. Further analysis casts doubt on this, as these effects may be because of object-tracking processes spilling over into the delay period, despite our efforts to equate the perceptual properties of each condition during the delay period. Anticipating the possibility of unwanted perceptual spillover from the tracking phase of each trial, we used two different cues for location change during the shuffling period (Figure 1), arrows and actual motion. We found stronger effects in these regions for trials involving arrows, rather than actual motion. The cuneus is a classic visual region in the occipital lobe (e.g., Vanni, Tanskanen, Seppä, Uutela, & Hari, 2001), and the subregion of the precuneus identified here appears to play an important role in object tracking (Kimmig et al., 2008; Shulman et al., 1999). In light of the above, we suggest that these belief-related results may be artifactual and require further investigation. We note, however, that we found no effect of cue type in the IFG for any analysis.

We also observed many regions that were preferentially activated for desire trials (*desire* > *belief* and *desire* > *think*). Given that desire in our task is elicited by the anticipation of a rewarding outcome, one might expect desire trials to elicit increased activity in regions associated with the anticipation of reward. However, we found no evidence of increased activation in classic reward-related regions such as the ventral striatum and orbital frontal cortex. This may be because we conducted our analyses during an extended delay period after the presentation of reward-relevant information. Instead, many of the regions that exhibited increased activity for desire trials lie within the default mode network (Raichle, 2015; Buckner, Andrews-Hanna, & Schacter, 2008). These include regions in the medial pFC, the inferior parietal lobule, and the middle temporal gyrus. We likewise observed desire-related activity in the dorsal attention network (Szczepanski, Pinsk, Douglas, Kastner, & Saalmann, 2013; Fox, Corbetta, Snyder, Vincent, & Raichle, 2006; Corbetta & Shulman, 2002), including subregions of the dorsolateral pFC. Although activity within these two networks tends to be anticorrelated (Fox, Zhang, Snyder, & Raichle, 2009), they can simultaneously exhibit increased activation during mental simulations of future goal-directed action (Stawarczyk & D'Argembeau, 2015; Gerlach, Spreng, Madore, & Schacter, 2014; Gerlach, Spreng, Gilmore, & Schacter, 2011). Although participants could not take action to increase their probability of reward in this task, desire may naturally elicit thoughts about future behavior. Consistent with this idea, many of these regions have also been implicated in the valuation of imagined possibilities (Bulley, Henry, & Suddendorf, 2016; Benoit, Szpunar, & Schacter, 2014), and episodic simulation more generally (De Brigard, Addis, Ford, Schacter, & Giovanello, 2013; Schacter et al., 2012; Addis, Pan, Vu, Laiser, & Schacter, 2009).

Finally, our multivariate analyses yielded only one significant finding: target location encoding across attitude conditions in the visual cortex. This most likely reflects a shift of attention to the target location. We were unable to reliably decode the identity of the target objects across conditions, or within condition. The target object is not visible to participants during the critical delay period in our task, making it unlikely that object identity would be decodable in visual regions. Some studies report decoding object identity from visual working memory (e.g., Emrich, Riggall, LaRocque, & Postle, 2013; Riggall & Postle, 2012; Christophel, Hebart, & Haynes, 2012; Harrison & Tong, 2009), but others failed to do so (Olmos-Solis, van Loon, & Olivers, 2021; Linden, Oosterhof, Klein, & Downing, 2012).

Here, we introduced a new task, the shell game, to examine the neural mechanisms of belief, desire, and mere thought in a controlled fashion. This task, however, is somewhat artificial and focuses on propositional content related to concrete states of affairs (objects and their locations) with information presented visually and (primarily) nonverbally. It is unknown whether the present results will generalize to verbal presentation of information and/or to information presented in other sensory modalities (e.g., auditory). Likewise, it is unknown whether these results will generalize to propositional attitudes related to the social domain (e.g., "Caitlin is married to Elizabeth," "James has three children") and to abstract propositions more generally (e.g., "Inflation is rising in the United States," "God exists"). Although propositional attitudes toward many such propositions would be difficult to control experimentally, our experimental paradigm could be adapted to examine beliefs, desire, and mere thoughts about more abstract states of affairs and to propositional attitudes generated by verbal stimuli. We view these as important directions for future research.

Here, we have presented evidence for the Spinozan account of belief (Gilbert et al., 1993; Gilbert, 1991; Spinoza, 1677/1982). Although the Spinozan view predates Darwin, it has a natural evolutionary explanation. Automatically believing information presented by the environment will be adaptive in an environment in which most of the available information is accurate (Mandelbaum & Quilty-Dunn, 2015; Levine, 2014; Kissine & Klein, 2013; Reber & Unkelbach, 2010; Levine et al., 1999). Before the advent of language, when beliefs were based entirely on typically veridical perceptions, this assumption may have held (Mandelbaum & Quilty-Dunn, 2015; Mandelbaum, 2014). However, the capacity for language opens human minds to a vast sea of ideas—some true, some false. Humans have the useful ability to form accurate beliefs about things far beyond their personal experiences, but humans are also highly susceptible to misinformation, whether intentional or unintentional (Van Der Linden, 2022). This creates a need for a cognitive "spam filter," a mechanism for entertaining ideas without believing them.

If humans have a unique (or uniquely prominent) need for "unbelieving" thanks to language, this naturally raises questions about what happens when the unbelieving process is compromised. Schizophrenia and related mental disorders involve delusions, beliefs that are firmly held despite disconfirmatory evidence (American Psychiatric Association, 2013). We suggest that delusion may be understood as a failure of Spinozan unbelieving, which we propose may involve a failure of inhibitory control. It is likely that delusions are not merely the result of failed inhibitory control, as many disorders involving failures of inhibitory control do not involve delusions (e.g., attention deficit hyperactivity disorder; Quay, 1997). However other evidence suggests that delusions have an inhibitory component, as patients with schizophrenia exhibit accelerated semantic spreading (Kreher, Goff, & Kuperberg, 2009; Moritz, Woodward, Küppers, Lausen, & Schickel, 2003; Spitzer, Braun, Hermle, & Maier, 1993; Maher, Manschreck, Hoover, & Weisstein, 1987) and a tendency to jump to unwarranted conclusions (Dudley et al., 2016; Evans et al., 2015; Moritz & Woodward, 2005). Delusions are difficult to study because the formation of delusional belief typically occurs outside the laboratory and without control of the available information. We suggest that the shell game paradigm may be used to study the process of belief formation in clinical populations and to test the hypothesis that delusions result from a failure of Spinozan unbelieving. More generally, however, the shell game paradigm provides a method for studying the mechanisms of propositional attitudes in controlled fashion, with the ability to dissociate propositional attitudes from propositional content.

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Data Availability Statement

Imaging data are available upon request from the corresponding author.

Author Contributions

Regan Bernhard: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Software; Visualization; Writing—Original draft; Writing—Review & editing. Steven Frankland: Conceptualization; Formal analysis; Investigation; Methodology; Software; Writing—Review & editing. Dillon Plunkett: Data collection and analyses; Revisions; Writing. Beau Sievers: Formal analysis; Writing—Review & editing. Joshua Greene: Conceptualization; Investigation; Methodology; Supervision; Visualization; Writing—Original draft; Writing—Review & editing.

Diversity in Citation Practices

Retrospective analysis of the citations in every article published in this journal from 2010 to 2021 reveals a persistent pattern of gender imbalance: Although the proportions of authorship teams (categorized by estimated gender identification of first author/last author) publishing in the *Journal of Cognitive Neuroscience* (*JoCN*) during this period were M(an)/M = .407, W(oman)/M = .32, M/W = .115, and W/W = .159, the comparable proportions for the articles that these authorship teams cited were M/M = .549, W/M = .257, M/W = .109, and W/W = .085 (Postle and Fulvio, *JoCN*, 34:1, pp. 1–3). Consequently, *JoCN* encourages all authors to consider gender balance explicitly when selecting which articles to cite and gives them the opportunity to report their article's gender citation balance. The authors of this article report its proportions of citations by gender category to be as follows: M/M = .62; W/M = .26; M/W = .075; W/W = .075.

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