



Projecting one's own spatial bias onto others during a theory-of-mind task

Branden J. Bio^a, Taylor W. Webb^a, and Michael S. A. Graziano^{a,1}

^aDepartment of Psychology, Princeton University, Princeton, NJ 08544

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Many people show a left-right bias in visual processing. We measured spatial bias in neurotypical participants using a variant of the line bisection task. In the same participants, we measured performance in a social cognition task. This theory-of-mind task measured whether each participant had a processing-speed bias toward the right of, or left of, a cartoon agent about which the participant was thinking. Crucially, the cartoon was rotated such that what was left and right with respect to the cartoon was up and down with respect to the participant. Thus, a person's own left-right bias could not align directly onto left and right with respect to the cartoon head. Performance on the two tasks was significantly correlated. People who had a natural bias toward processing their own left side of space were quicker to process how the cartoon might think about objects to the left side of its face, and likewise for a rightward bias. One possible interpretation of these results is that the act of processing one's own personal space shares some of the same underlying mechanisms as the social cognitive act of reconstructing someone else's processing of their space.

visuospatial bias | social cognition | theory of mind | spatial perception | line bisection

Many people show a left-right bias in visual processing (1–4). Averaged across a population, the bias is usually toward the left, but individuals vary, with some people exhibiting a left bias and others exhibiting a right bias. In the present study, we asked whether this bias in one's own spatial processing is mirrored in one's social cognition. If you are biased toward processing your own right side of space, are you also faster at recognizing when someone else processes an object to his or her right side? The idea that one's own spatial limitations are reflected in one's social perceptions has been suggested before (5).

Each participant was tested on two tasks. One task was a variant of the line bisection task (1–4), used to measure the participant's spatial bias. The second task was a modified theory-of-mind task (6), used to measure the participant's social cognition toward a cartoon character. The participant had to decide whether the cartoon character “thought” that a ball was in box 1 or box 2. Box 1 was to the left and box 2 to the right of the cartoon character. Crucially, the cartoon was rotated such that what was left and right with respect to the cartoon was up and down with respect to the participant. Thus, the participant's own left-right bias did not directly align with left and right with respect to the cartoon head. Reaction times were measured in the theory-of-mind task, and we assessed whether participants were faster at responding when the cartoon character supposedly processed an object to its left or its right.

The false-belief task has become a common tool to test social cognition (6–8). It typically interleaves two trials types: true belief and false belief. In the task used here, in the false-belief trials (when the participant can see that the ball is in one box but the cartoon character, whose vision is blocked, should think it is in the other box), solving the task requires social cognition. The participant must consider what the cartoon character believes rather than what is literally true. However, in the true-belief

trials (when the participant can see that the ball is in one box and the cartoon character has also “seen” it in the same box), the participant could in principle determine the trial type by low-level cues (such as the absence of a barrier blocking the cartoon character's sight) and then solve the task without imputing any specific belief to the character. The participant could report which box the ball is actually in, thus performing a simple visual task, without ever considering which box the character “thinks” it is in. The true-belief trials therefore might or might not involve some level of social cognition. Only the false-belief trials ensure that the participant engages in social cognition.

For these reasons, in the present experiment, we made a prediction with respect to the false-belief trials. We predicted that people who had a natural bias toward processing their own left side of space would be quicker to respond when the cartoon thinks an object lies to the left side of its face, and likewise for a rightward bias. This relationship was predicted specifically for the false-belief trials in the theory-of-mind task. In the true-belief trials, in which social cognition could not be ensured, we could not make a similar prediction, but the outcome may still provide useful information or insightful interpretation.

Methods

Participants. All participants provided informed consent, and all procedures were approved by the Princeton Institutional Review Board. Seventy-nine participants were tested (55 women, 18–55 y old, median age = 21, normal or corrected-to-normal vision). Each participant performed two tasks: the line bisection task and the theory-of-mind task. The order of tasks was randomized between participants. Criteria for excluding participants, based on task performance, are described below in the sections specific to each task.

Participants sat stabilized by a chinrest 30 cm from a computer screen and used keypresses on a standard keyboard for behavioral responses. Visual stimuli were presented on the screen using Matlab and the Psychophysics Toolbox (9, 10).

Significance

Most people have an intrinsic spatial bias—many are better at processing objects to the left, whereas some are biased to the right. Here, we found that this subtle bias in one's own awareness is mirrored in one's ability to process what is likely to be in other people's minds. If you are biased toward processing your own right side of space, then you may be faster at recognizing when someone else processes an object to his or her right side. One possible interpretation is that we process the space around us, and understand how others process the space around them, using at least partially shared mechanisms.

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¹To whom correspondence should be addressed. Email: graziano@princeton.edu.

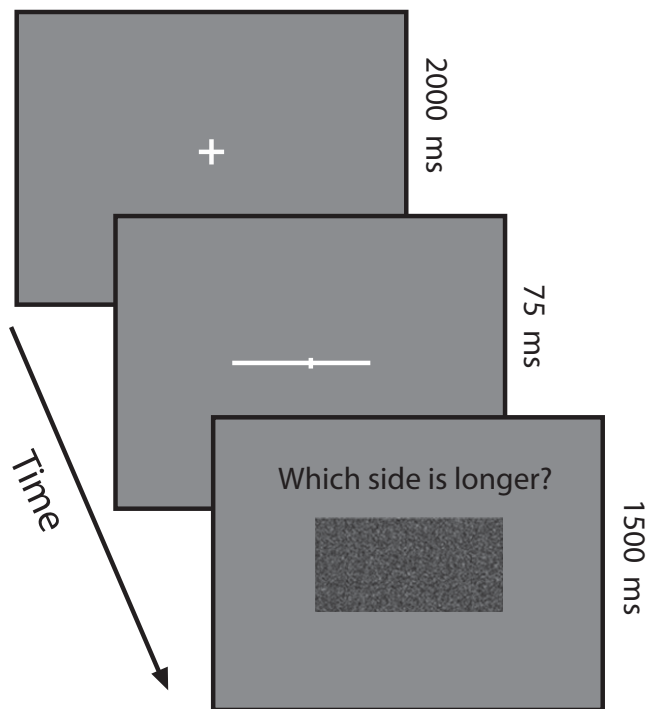


Fig. 1. Paradigm for the line bisection task. Participants saw a brief presentation of a transected line and judged which side was longer. See text for details.

Line Bisection Task. In cases of clinical neglect caused by brain damage, patients are often tested with the line bisection task (11–13). The patient is given a piece of paper with a long horizontal line and asked to draw a vertical transector that bisects the line. A patient with left-sided neglect will typically draw the transector to the right of true center, as though the longer left side appears shortened. In the nonclinical population, a simple line bisection test is typically not sensitive enough to detect a visuospatial bias. A speeded variant of the task is often used, sometimes called a landmark task (1–4). Fig. 1 shows the paradigm used, modified from Szczepanski and Kastner (3).

Each trial began with a white fixation cross on a gray background. Participants were instructed to fixate on the cross. After 2,000 ms, the cross disappeared and a white horizontal line with a vertical transecting line was displayed for 75 ms. The reason for the brief display was that people are typically extremely sensitive to the left-right asymmetry used in this task. In pilot tests, we settled on a presentation time that reduced performance and resulted in a useful psychophysical curve (see description of curve fitting below).

The vertical transecting line was 2° tall in visual angle and was always displayed at the midline of the screen. The horizontal line could be one of four lengths (20, 21, 22, or 23°) and was positioned at one of 11 possible offsets (centered, or offset to the left or right in 0.2° increments, with a maximum offset of 1°). Thus, 44 stimulus configurations were possible.

After the 75-ms display of the transected horizontal line, a rectangular visual mask (random black and white pixels, 28° in width by 14° in height) covered the area where the stimulus had been. The purpose of the mask was to reduce performance to a range in which a useful psychometric curve could be obtained. Above the mask, a question was presented: “Which side is longer?” Participants were instructed to respond by pressing one of two keys on a keyboard to indicate whether the horizontal line was longer on the left or right of the vertical transector, and were given 1,500 ms to respond. Trials where participants exceeded the response window were not included in analyses. Participants responded on most trials (99.6%). After the response window, the next trial began immediately.

Participants performed 176 trials in 4 blocks of 44 trials each. All trial types were balanced and randomly interleaved. The 4 line lengths and 11 offsets yielded 44 trial types. However, trials corresponding to different line lengths were collapsed together during analysis, yielding 11 analysis conditions. Thus, participants performed 16 trials per condition. The task typically required 5 min to complete.

Fig. 2 shows data from one participant to illustrate the analysis method (for group data, see *Results*). The goal of the analysis was to determine, for each participant, the left-right spatial bias in judging line bisection. The x axis shows the 11 possible offsets of the horizontal line with respect to the

transector, and the y axis shows the proportion of trials that the participant reported the line to be longer on the left. The data were fitted to a logistic function whose maximum and minimum were fixed at 1 and 0, respectively. The midpoint of the logistic function, the point at which the curve crossed a height of 0.5, is indicated in the figure by a dotted vertical line. The x value of the midpoint was taken as a measure of the participant’s left-right bias, the point at which the participant psychophysically judged the horizontal line to be bisected. Following the standard interpretation of line bisection performance, if the horizontal line was longer on the left when the participant judged it to be bisected, then the participant was inferred to have a rightward spatial bias; likewise, if the horizontal line was longer on the right when the participant judged it to be bisected (as in Fig. 2), then the participant was inferred to have a leftward spatial bias.

To provide an estimate of the quality of the curve fit for each participant, an *r*-squared value was computed. Only participants with an *r*-squared of 0.8 or higher were included in the final analysis, to increase the likelihood of obtaining a reliable measure of spatial bias for each individual participant. This criterion eliminated 21 of 79 participants. We recognize that this cutoff represents a large exclusion. However, the central hypothesis of the study could not be tested without a reliable measure of spatial bias for each individual participant. A noisy or unreliable measure that failed to distinguish left from right bias would render the hypothesized relationship between the two tasks difficult or impossible to detect.

Theory-of-Mind Task. Theory-of-mind reasoning is often tested with the false belief task first introduced by Wimmer and Perner (6). In the typical task, participants are presented with a vignette: Sally watches as a sandwich is placed in one of two boxes. Sally then goes away. During her absence, the sandwich is moved to the other box. When Sally returns, which box will she check for the sandwich? Solving the task requires an understanding that Sally has a mind, that her mind contains beliefs about the world, and that she can hold beliefs that are contrary to fact (6–8).

In the modified task that we used, participants saw a cartoon that included people, boxes, and a ball. The ball was located in one of two boxes and the participant had to decide whether a cartoon person would most likely believe the ball to be in box 1, to the left of the cartoon person, or box 2, to the right. We used a reaction time measure to determine if the participant demonstrated a spatial processing bias toward the cartoon person’s left or right. As detailed below, to convert the paradigm to a reaction time task, we presented participants with two cartoon people at the same time. Participants

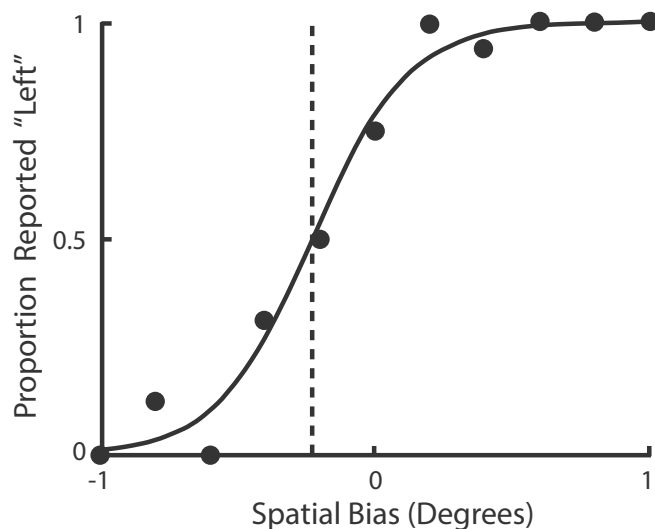


Fig. 2. Results of the line bisection task for one participant to illustrate analysis method. x axis shows the visual degrees by which the horizontal line was longer on the left side of the transector. y axis shows the proportion of trials the participant reported the horizontal line to be longer on the left. The data were fitted with a logistic function. The dotted line shows the half-height point on the curve, the psychophysical point at which the participant appeared to judge the line to be bisected. This participant had a negative, or leftward, spatial bias (the participant judged the line to be bisected when the right side was actually longer).

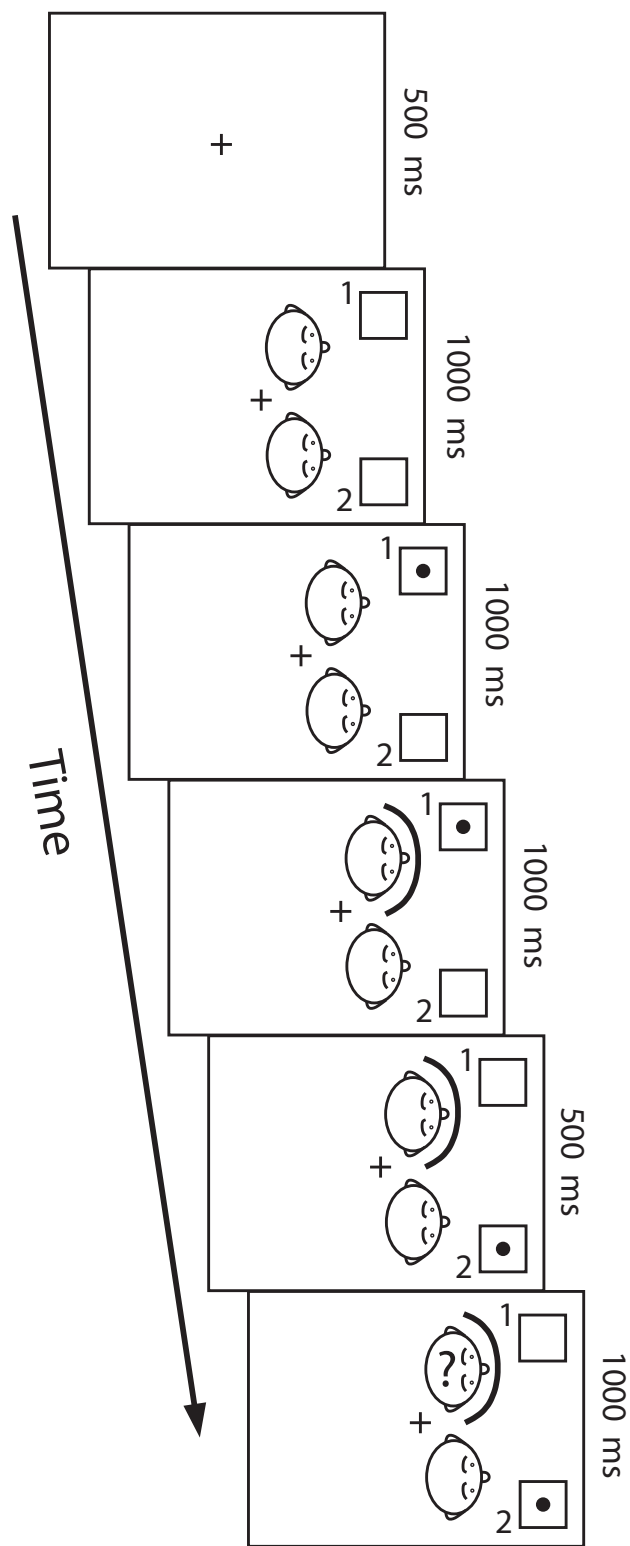


Fig. 3. Paradigm for the theory-of-mind task. Participants saw a sequence of cartoon panels showing two heads viewing a ball that could be placed in either of two boxes. One of the heads had its vision blocked partway through the trial. In the final image, one head was indicated by a question mark. Participants were instructed to respond as quickly as possible, judging whether the indicated head would think the ball was in box 1 or box 2. See text for details.

responded only at the end of the trial when one of the two cartoon people was indicated as the target for the theory-of-mind judgment.

Fig. 3 shows the paradigm. Each trial began with a black fixation cross at the center of a white background. Participants were instructed to fixate on the cross. After 500 ms, the fixation cross was joined by a top-down view of two cartoon heads and two numbered boxes. The heads and boxes were arranged vertically with respect to the participant, such that the left-right axis with respect to the cartoon heads was orthogonal to the left-right axis with respect to the participant. In this way, the participant's own left-right cognition bias toward the left or right of the cartoon head.

The heads were 5° right of the vertical midline of the screen, facing toward the right, centered 5° above and below the midpoint of the screen. The boxes were 23° to the right of the midpoint of the screen, centered 15° above and below the horizontal midline. After 1,000 ms, a red ball appeared in one of the two boxes (half of the trials in box 1; half of the trials in box 2). Participants had been told in the instruction period that, in this configuration, both heads could see where the ball was located. After 1,000 ms, one of the heads was blocked with a curved partition directly in front of it (half of the trials blocking the upper head, half of the trials blocking the lower head). Participants had been told in the instruction period that the blocked head could no longer see either the boxes or the ball, but that the other head could still see everything as before.

In half the trials, 1,000 ms after the partition appeared, the ball switched position to the opposite box. If it was initially in box 1, it moved to box 2; if it was initially in box 2, it moved to box 1. Thus, the head that was blocked should "believe" the ball to be in the original box and the head that was unblocked should "see" the ball move to the new box. In the other half of trials, the ball did not switch positions.

Finally, 4,000 ms after the start of the trial, a question mark appeared inside one of the heads (half of trials in the upper head, half of trials in the lower head). The question mark indicated which head was to be the target of the participant's judgment. The participant was instructed to respond as quickly as possible once the question mark appeared. By pressing one of two buttons on a standard keyboard, the participant reported whether the indicated head would most likely think the ball was in box 1 or box 2. Participants were allowed a response window of 1,000 ms. Trials on which

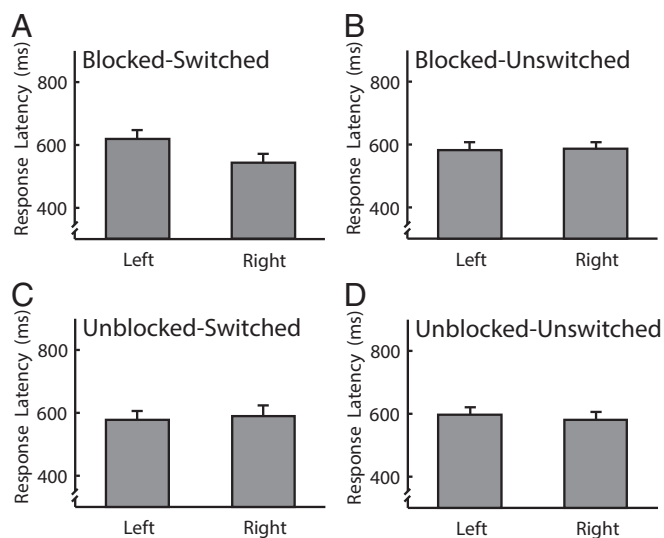


Fig. 4. Result of the theory-of-mind task for one participant, to illustrate analysis method. y axis shows mean response time. The ball remained in the same box (unswitched trials) or switched to the opposite box (switched trials). The cartoon head indicated by the question mark was the one not blocked by the screen (unblocked trials) or was the one blocked by the screen (blocked trials). The correct answer could be the box that was to the left of the head ("left" trials) or the box that was to the right of the head ("right" trials). (A) This participant showed a latency difference in the blocked-switched condition, with an advantage in processing the right side with respect to the cartoon head. (B) No significant latency difference was found in the blocked-unswitched condition for this participant. (C) No significant latency difference was found in the unblocked-switched condition. (D) No significant latency difference was found in the unblocked-unswitched condition.

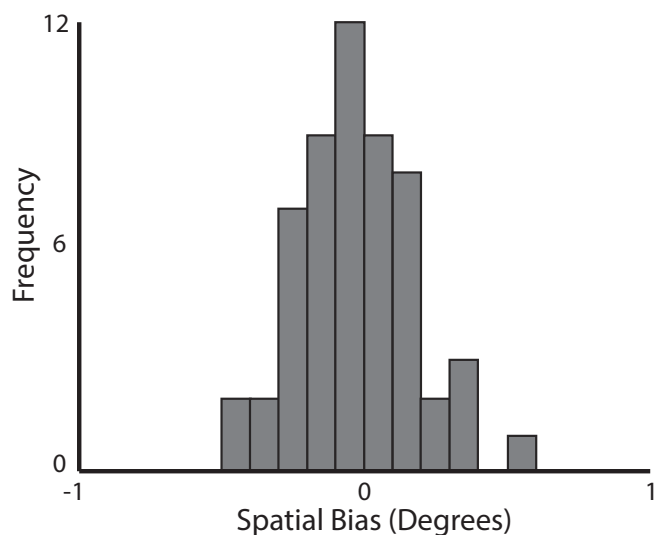


Fig. 5. Frequency histogram showing the spatial bias, measured in the line bisection task, among 55 participants. Although individual participants showed a spatial bias, the sample as a whole showed no significant overall left or right bias (two-tailed t test, $t = 1.22$, $df = 54$, $P = 0.220$).

participants exceeded the given time to respond were not included in the analyses, although participants responded on most trials (95%). After the response window, the display of heads and boxes disappeared and the next trial began with the onset of the fixation cross.

Participants performed 256 trials, in 8 blocks of 32 trials each. The task took 20–30 min to complete. The task included the following conditions: The ball could be initially presented in box 1 or box 2; the blocking screen could be placed in front of the upper or lower head; the ball could be switched to the opposite box or remain in the same box; and the question mark could be presented in the upper or lower head. This $2 \times 2 \times 2 \times 2$ design resulted in 16 trial types, presented in a counterbalanced and randomized order.

Fig. 4 illustrates the analysis by showing data from one participant (for group data, see *Results*). The trial types were collapsed into four conditions for purposes of analysis, 64 trials per condition. These conditions formed a 2×2 design as follows: the ball remained in the same box (“unswitched” trials) or switched to the opposite box (“switched” trials), and the head indicated by the question mark was the one not blocked by the screen (“unblocked” trials) or was the one blocked by the screen (“blocked” trials). For each of these four conditions, the correct answer could be box 1 (the box that was to the left of the head) or box 2 (the box that was to the right of the head). As shown in Fig. 4 for one subject, a mean reaction time was computed for each of those conditions. A reaction time difference score was then computed [difference score = (mean reaction time for the left-box trials) – (mean reaction time for the right-box trials)]. A positive score indicated a faster reaction time when the right box was the correct answer and, thus, a right-sided preference. This difference score was computed for each of the four main conditions for each participant. For example, in Fig. 4, the participant had a right preference in the blocked-switched condition, but little or no preference in the other three conditions.

The blocked-switched condition corresponded to a false belief condition (the participant could see the ball was in one box but the cartoon character should think the ball is in the other box). The other three conditions corresponded to true-belief conditions (the participant could see the ball was in one box and the cartoon character should think the ball is in the same box).

Most participants performed at high accuracy (mean of 86% of trials correct). Only correct trials were included in the analysis. Three subjects were removed from analysis due to below-chance performance suggesting that they had not understood the instructions. Given this removal, and the removal of participants based on curve-fit criteria in the line bisection task, we had a final set of 55 participants in which the performance on the two tasks could be compared (39 female, age 18–55 y, median age of 21).

Results

Line Bisection Task. For each participant, a spatial bias was computed. As described in *Methods* and illustrated in Fig. 2, we used

a logistic curve fit to obtain the point at which the participant appeared to judge a horizontal line to be bisected by a vertical line. Following the standard interpretation of line bisection performance, if the point of perceptual bisection corresponded to a longer left side, the participant was inferred to have a spatial bias in favor of the right. If the right side was longer, the participant was inferred to have a spatial bias in favor of the left. Fig. 5 shows the distribution of spatial biases among 55 participants. Although each individual participant may have shown a spatial bias (such as the left-biased participant illustrated in Fig. 2), the overall distribution was not significantly different from zero, but slightly shifted toward the left (mean = -0.03° , SEM = 0.03, two-tailed t test, $t = 1.22$, $df = 54$, $P = 0.220$), indicating that neither a left nor a right bias predominated in this sample. This finding is not inconsistent with previous findings that the average spatial bias can be subtle and variable across studies (2). The focus of the present study was not on the average bias, however, but on how individuals’ spatial biases corresponded between the two tasks.

Of the 55 participants, 32 showed a left bias and 23 showed a right bias. These two groups did not differ significantly in number of left-handed individuals (four in each group), in magnitude of spatial bias, or in their reaction times as measured during any of the eight specific trial types in the theory-of-mind task denoted in Fig. 4 (t test, $P > 0.05$).

Theory-of-Mind Task. In the theory-of-mind task, on each trial, a reaction time was measured. The mean reaction time for all trials was 593 ms (SEM = 10.5). As described in *Methods* and illustrated in Figs. 3 and 4, the task included four conditions corresponding to a 2×2 design. The blocked-switched condition corresponded to a false-belief condition (in which the cartoon character should believe the ball to be in one box when it is actually in another). The other three conditions were true-belief conditions (in which the cartoon character should believe the ball to be in the box that it is actually in). Table 1 shows the mean reaction times in these four conditions. An ANOVA indicated that there was a significantly greater reaction time for switched trials than for unswitched trials (within subjects 2×2 ANOVA, $F = 13.80$, $P = 0.0003$), presumably because of the extra cognitive cost of processing the switched ball location. There was no significant difference between blocked and unblocked trials, and no significant interaction (main effect of blocked vs. unblocked, $F = 3.53$, $P = 0.062$; interaction, $F = 0.13$, $P = 0.714$). The focus of this experiment, however, is not on the group statistics but on how individual spatial biases corresponded between the two tasks. In each condition, for each participant, a reaction time difference score was obtained. The difference score corresponded to a spatial bias, with a positive score corresponding to a rightward bias with respect to the cartoon head. The relationship between this spatial bias and the bias measured in the line bisection task is described in the next section.

Correspondence Between Tasks. Fig. 6A shows how the spatial bias measured in the line bisection task relates to the spatial bias measured in the false-belief condition of the theory-of-mind task. The two measures are significantly, positively correlated (linear regression, Beta = 0.77, $F = 6.26$, $P = 0.016$), thus supporting the prediction.

Table 1. Mean reaction times in the four conditions of the theory-of-mind task

Conditions	BS	BnS	nBS	nBnS
Mean	618.74	563.89	639.07	594.08
SEM	11.75	16.25	10.12	14.75

Times shown in milliseconds. See text for statistical results of ANOVA. BnS, blocked, not-switched condition; BS, blocked, switched condition; nBnS, not-blocked, not-switched condition; nBS, not-blocked, switched condition.

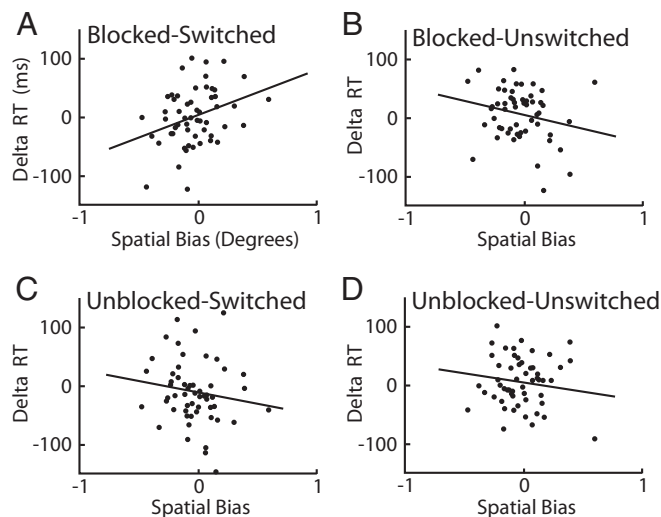


Fig. 6. Regression plots relating the line bisection results to the theory-of-mind results in 55 participants. The x axis shows the spatial bias for each participant, measured in degrees of visual angle using the line bisection task. The y axis shows the participant's bias toward the left or right of the cartoon head, measured in the theory-of-mind task, using a difference of reaction times (delta RT). (A) Spatial bias versus theory-of-mind performance in the blocked-switched condition. Each point shows the results for one participant. The regression line is significant ($\text{Beta} = 0.77$, $F = 6.26$, $P = 0.016$). Because this condition was the only one to require true theory-of-mind reasoning, this regression is the crucial test of the hypothesis. (B–D) Similar plots for conditions in which theory-of-mind reasoning was not required to solve the task. These regression lines were not significant (B, $\text{Beta} = -0.48$, $F = 2.79$, $P = 0.101$; C, $\text{Beta} = -0.39$, $F = 1.20$, $P = 0.279$; D, $\text{Beta} = -0.31$, $F = 0.85$, $P = 0.360$).

As shown in Fig. 6 B–D, in the three true-belief conditions that did not necessitate theory-of-mind reasoning, the correlations were nonsignificant and trended in a negative direction (unblocked-unswitched: $\text{Beta} = -0.48$, $F = 2.79$, $P = 0.101$; unblocked-switched: $\text{Beta} = -0.39$, $F = 1.20$, $P = 0.279$; blocked-unswitched: $\text{Beta} = -0.31$, $F = 0.85$, $P = 0.360$).

Discussion

The present study tested participants in two tasks: a line bisection task and a theory-of-mind task. The line bisection task measured whether each participant had a visuospatial bias toward the right or left. The theory-of-mind task measured whether each participant had a processing-speed bias along an orthogonal axis, toward the right of, or left of, the agent about which the participant was thinking. Performance on these two tasks was significantly correlated. The correlation was specific to the one condition in the theory-of-mind task that required social cognition, the false-belief condition. One possible interpretation is that the participants exhibited a spatial bias in the theory-of-mind task because, when social cognition was engaged, the participants were reconstructing a left-right frame of reference with respect to the cartoon character.

An alternative explanation for the observed relationship is that people might have both a horizontal and a vertical spatial bias,

and a leftward bias might generally tend to correlate with an upward bias. This explanation is unlikely, given the previous finding that left-right and up-down spatial biases do not correlate (14). This alternative explanation is also inconsistent with the present findings, in which the relationship could be seen only for the false-belief condition in the theory-of-mind task, and not for the three true-belief conditions. The true-belief conditions did not show any significant correlation with the line bisection task. The results are more consistent with the interpretation that in the true belief conditions, because the same level of social cognition was not necessary to solve the task, participants may have taken a cognitive shortcut, or may have engaged social cognition to a lesser extent. In that case, on true-belief trials, the participants might not have actively conceptualized the ball in relation to the cartoon head and, therefore, their own left-right processing bias would not have been engaged.

The results are consistent with studies on perspective taking, in which people mentally rotate themselves into the spatial perspectives of others to judge the perceptual world of others (15–17). The results may also relate to the finding that reaction times in a theory-of-mind task are faster when the participant and the character share the same mental state (18). One's own mental state, beliefs, or spatial processing limitations may be mirrored in how one attributes mind states to others.

The line bisection task was originally used to measure a severe spatial bias in the clinical syndrome of hemispatial neglect (11–13). In these cases, the patient's attention and awareness of one side of space is compromised. In neurotypical participants, the line bisection task is thought to measure a subtler spatial bias in attention to or awareness of the two sides of space (1–4). In the theory-of-mind task in the present experiment, the participant is effectively attributing to the cartoon agent an attention to, or an awareness of, the ball in a specific location. We speculate that the mechanisms by which people spatially direct attention and awareness may partially overlap the mechanisms by which people attribute such mind states to others (5, 19). The cortical networks that appear to be involved in these different functions show substantial anatomical overlap, especially where they pass through the temporoparietal junction (TPJ). Damage to this region, especially on the right side, can lead to the most severe cases of hemispatial neglect (20). However, regions within the TPJ are also consistently recruited in studies of social cognition. Theory-of-mind tasks and perspective taking tasks activate at least some subregions within the TPJ (15, 21, 22). A complex experimental literature suggests that the TPJ is composed of many functional subregions, with some separation and some overlap of function (23–27). Although the full extent of anatomical overlap and separation is not yet resolved, it appears that social, attentional, and awareness-related networks pass close to each other with partial overlap in the TPJ. It is possible that this anatomical and functional overlap contributes to the present findings in which one's own limitations in spatial processing are mirrored in one's social cognition.

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