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Spontaneous vicarious perception of the content of another's visual perspective

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Summary

Visual perspective taking (VPT) is a core process of social cognition, providing humans with insights into how the environment looks from another's point of view [1-4]. While VPT is often described as a quasi-perceptual phenomenon [5,6], evidence for this proposal has been lacking. Here we provide direct evidence that another's perspective can "stand in" for own sensory input perceptual decision-making. In a variant of the classic mental rotation task, participants judged whether characters presented in different orientations were canonical or mirror-inverted. In the absence of another person, we replicate the well-established positive linear relationship between recognition times and angle of orientation, such that recognition becomes slower the more an item has to be mentally rotated into its canonical orientation [18]. Importantly, this relationship was disrupted simply by placing another individual in the scene. Items rotated away from the participant were recognised more rapidly not only the closer they appeared in their canonical orientation to the participant but also to this other individual, showing that another's visual perspective drives mental rotation and item recognition in a similar way as one's own. The effects were large and replicated in the three independent studies. They were observed even when the other person was completely passive, enhanced for explicit instructions to perspective-take, but reduced when the persons in the scenes were replaced with objects. The content of another's perspective is therefore spontaneously derived, takes a quasi-perceptual form, and can stand in for own sensory input during perceptual decision-making.

Keywords: *Perspective taking; visuospatial perspective taking, mental rotation; mental imagery, imagery, perceptual decision making, perceptual simulation.*

Results

Visual perspective taking (VPT) lies at the core of the ability to make sense of other people. It allows one to derive not only which objects can be seen from another's perspective (Level 1 VPT), but also *how* these objects will look to them (Level 2 VPT) [1,2]. It is a phylogenetically recent, human-specific ability that forms an important milestone during development and is linked to more sophisticated mentalizing abilities, such as empathy or theory of mind [2-4]. People rely on it regularly to judge how fellow drivers will respond to a difficult situation on the road, how their dance moves will be seen by others, or how to best show an object to a child so that they can recognise it easily, for example.

A recent proposal is that VPT takes a (quasi-)perceptual form, "painting" a mental image of the content of another person's viewpoint onto one's perceptual system that can stand in for one's own perception [5,6]. In such a view, VPT not only remaps the other's spatial reference frame to one's own (e.g. that one's own left is another's right) but derives their view on an object as if one would perceive it oneself. "Seeing" the content of another's perspective in this manner could then – in a bottom-up fashion – drive all processes that operate on perceptual input [7] so that one's own faculties for decision making can be deployed to predict how the person will behave [8-11]. Few, if any, studies have tested this proposal, however. While people can intentionally rotate their own body into another's perspective if so instructed [5,12], implicit measures only show general interference when making judgments that would be made differently from another's perspective [13-15], an effect that may index uncertainty when others would *respond* to a stimulus differently than oneself but not necessarily knowledge of how specifically they would *see* it. Moreover, these effects are only observed when the other person is at least somewhat task relevant (e.g. when sharing a task with them), leading to the proposal that, while there might be a fast, automatic mechanism that derives what others can see, deriving how they see it takes longer and is under (effortful) cognitive control [15-17].

Here, we tested whether humans have immediate, (quasi-)perceptual access to the content of another's viewpoint. We reasoned that a different perspective might then not only interfere with own judgments but *facilitate* them, specifically if these judgments would be easier from the other's perspective. In a variant of the mental rotation task [18] (Experiment 1a, *n*=34), participants simply judged in every trial whether alphanumeric characters appearing in different orientations on a table in front of them were in canonical form or mirror-inverted (e.g. "R" vs. "Я"). Typically, decision times increase the more an item is rotated away from the participant because it needs to be mentally rotated into an orientation from which it can be judged [18], a process that relies on pictorial (non-abstract) item representations in early sensory cortices [19,20]. Crucially, in 50% of trials, we inserted another person into the scene who would view the characters from either the participant's left or their right (Figure 1, Panel A). We hypothesized that if people have immediate, (quasi-) perceptual access to another's viewpoint, then recognition times for items rotated away from the participant should be faster if these items appear in a closer-to-canonical orientation *to this other person*, and can be better judged – or mentally rotated – from their perspective.

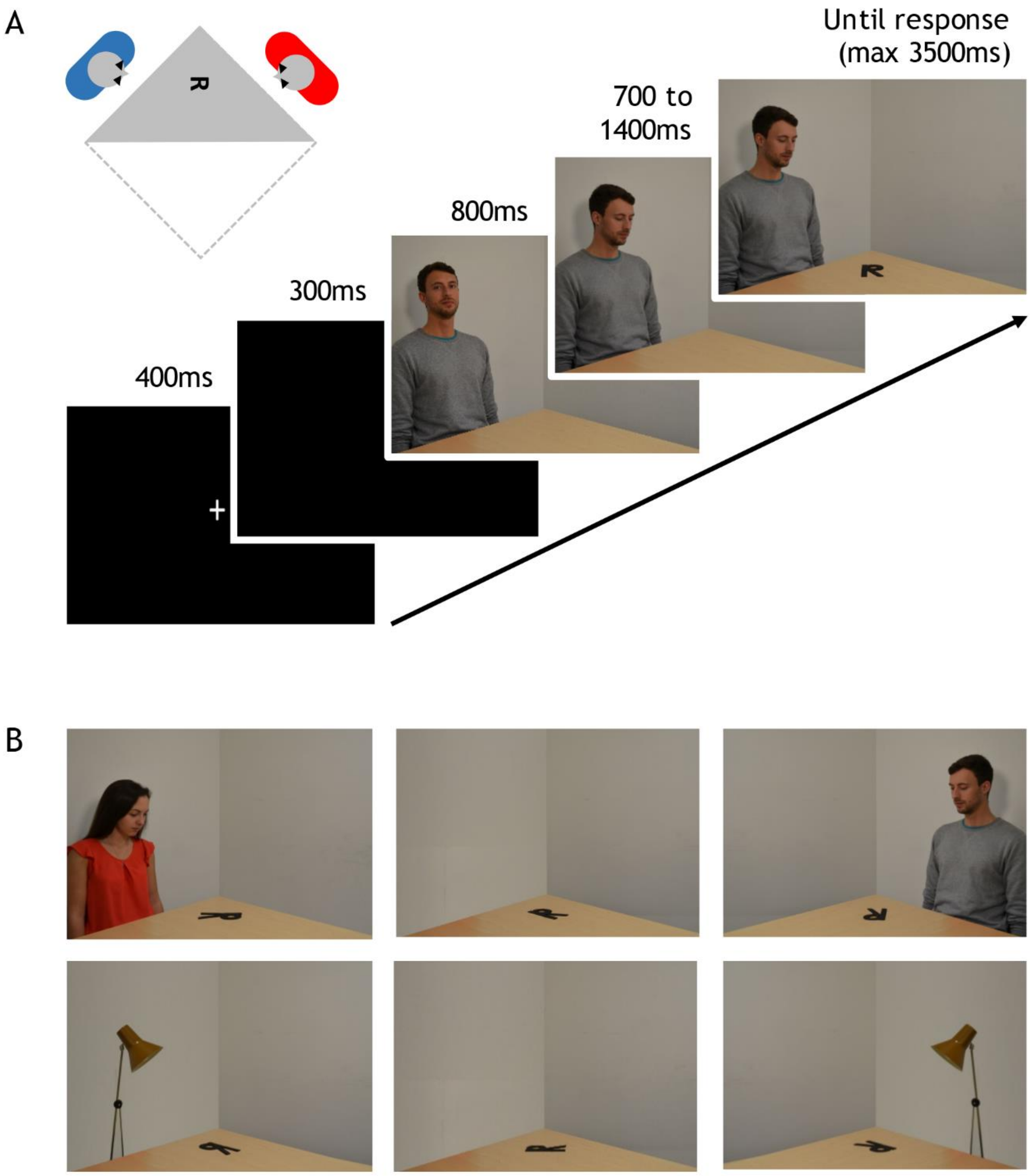

Figure 1. Schematic of the trial sequence and scene setup (A) in Experiment 1a and 1b and main conditions (B). Participants judged whether alphanumeric characters were presented canonically or mirror inverted (e.g., “R” vs. “Я”), depending on whether these items appeared in the presence of another person on the left (B, upper left), a person on the right (B, upper right), in the absence of another person (B, upper middle), or in the presence of a non-human object (B, lower panels, Experiment 2, manipulated between participants). See Figure S3 for camera setup and measurements of all stimulus items.

Person location systematically biases mental rotation curves

We first confirmed that our task replicates the mental rotation effect [18]. We derived a summary measure (Towards/Away-Bias) of how much faster characters are recognized the more they face the participant. For each participant and condition (No-human, Human-left, Human-right), we averaged the participant's mean response times for each character orientation, scaled by the negative of the cosine of the character orientation (see STAR Methods). Positive values therefore indicate slower responses the more an item is oriented away from the participant, and vice versa for negative values. As expected, simple t-tests revealed slower responses for characters oriented away rather than towards participants, in all three conditions, $t(33)>7.065$, $p<.001$, $d>1.21$ (Figure 2A, 2B). This mental rotation effect was also confirmed by regressing each item's recognition time to the expected linear increase with angular disparity [18], revealing positive slopes in all bar one participant, mean $\beta=1.01$; $t(33)=10.5$, $p<.001$, $d=1.80$.

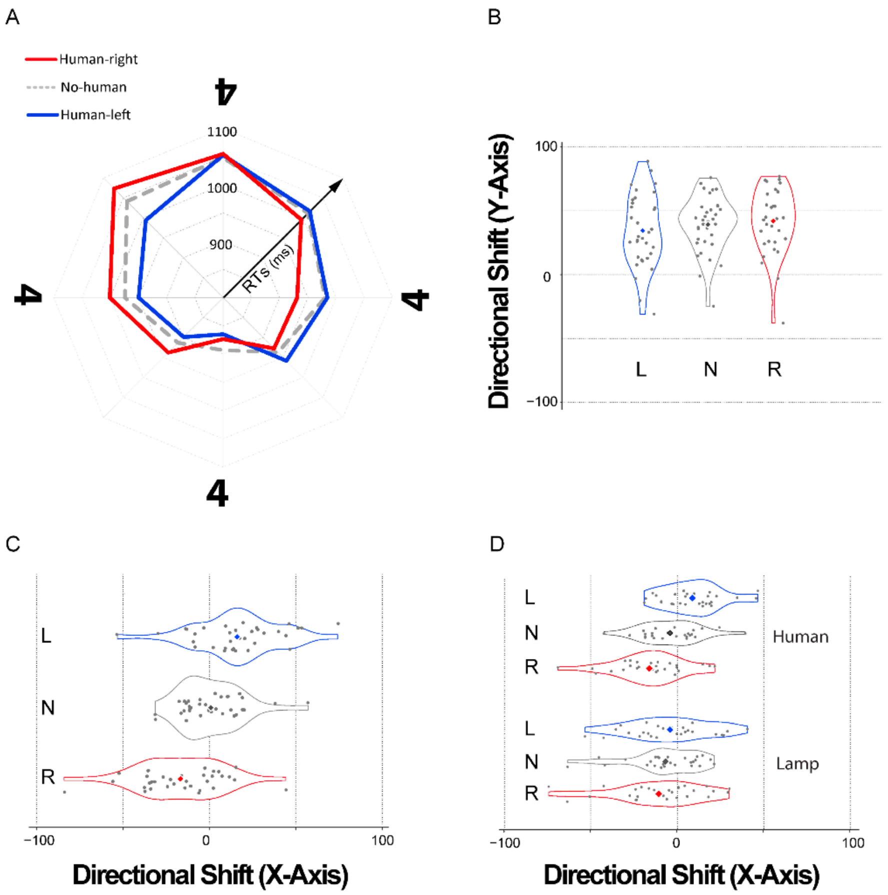

Figure 2. Results of Experiment 1a and 2: Person location systematically biases mental rotation curves. (A) Recognition times (ms) to correctly classify items as canonical or mirror-inverted in each of the eight orientations, depending on whether the person was absent, was sitting on the left, or was sitting on the right. B) Violin charts showing the Towards/Away-bias when the person was not present (N), was on the right (R), or was on the left (L); means are indicated by diamond symbols. (C) Violin charts showing the Left/Right-bias when the person was absent (N), was on the right (R), or was on the left (L); means are indicated by diamond symbols. (D) Results of Experiment 2: person location biases mental rotation curves more strongly than object (lamp) location. Violin charts showing the Left/Right-biases when a human (or lamp) was on the right (R), was not present (N), or was on the left (L); means are indicated by diamond symbols. See Figure S2 for the same data presented as line graphs, and Table S1 for error rate data.

The crucial test is whether shapes oriented away from the participant are easier to recognise if they appeared upright to the *other person*. We derived an analogous summary measure (Left/Right-bias, Figure 2A, 2C, see Figure S2A for mental rotation curves) indexing how much faster characters were recognised the more they were oriented left compared to right. For each participant and condition (No-human, Human-left, Human-right), we calculated the average recognition times, scaled by the sine of each character orientation. Positive values indicate slower recognition of right-oriented compared to left-oriented characters and vice versa for negative numbers. Directly comparing these values revealed substantial differences between Human-left and Human-right conditions, $t(33)=5.185$, $p<.001$, $d=.889$. As predicted, for persons on the left, left-oriented characters were recognised more quickly than right-oriented characters, $t(33)=3.584$, $p=.001$, $d=.614$, but vice versa for persons on the right, $t(33)=-4.074$, $p<.001$, $d=.698$. Both directional shifts differed from the (baseline) No-human condition, $t(33)>3.444$, $p<.002$, $d>.591$.

To test whether these biases reflect mental rotation from one's own *and* the other's perspective, we entered each participant's mean recognition times for all item orientations in the Human-Left and Human-Right condition into a multiple regression, with the item's angle to the participant and to the other person as two (statistically orthogonal) predictors. As expected, recognition times increased not only with the angular disparity to the participant, mean β=1.06, $t(33)$=9.92, p<.001, d=1.71, but also to the other person, mean β=.41, $t(33)$=4.92, p<.001, d=.84. Figure S2, top panels, shows the fit of recognition times (aggregated across all experiments) to the regression model and that they can be decomposed into two mental rotation functions from one's own and the other's perspective.

Replication

A replication study (Experiment 1b) with the same design (n=33) confirmed all findings (see Figure S1B). Towards/away-biases confirmed the mental rotation effect in all conditions, $t(32)$>7.723, p<.001, d>1.34. Left/Right biases differed between the Human-left and Human-right conditions, $t(32)$=-4.881, p<.001, d=.85, showing faster recognition of left-oriented than right-oriented characters in the Human-left condition, $t(32)$=-4.293, p<.001, d=.747, and vice versa for the Human-right condition, $t(32)$=-2,079, p=.046, d=.362. Both differed to the No-human (baseline) condition, $t(32)$>2.993, p<.005. Moreover, as before, recognition times increased linearly with the item's angle towards the participant, mean β=1.14, $t(32)$=9.30, p<.001, d=1.63, and towards the other person, mean β=.40, $t(32)$=5.76, p<.001, d=1.00.

Person location biases mental rotation curves more strongly than object location

Having established that another's perspective speeds up recognition of characters oriented towards this perspective, (Experiment 2, n=54) tested whether the same was true for non-human spatial reference points, i.e. 'mind-less' objects. For half of the participants, the persons in the images were replaced with a lamp that was similarly oriented towards the items on the table as the two individuals (and therefore provided similar directional cues towards it, Figure 1B, lower panels). To avoid imbuing the lamp with intentionality, all motion was removed from the stimuli. Lamps and other person did not initially “look” outwards at the participant and then back at the table, but started the trial already facing the location at which the character would appear.

As before, Towards/Away-biases confirmed the mental rotation effect, in all conditions of both groups, $t(27)>10.837$, $p<.001$, $d>2.05$, for all. To test whether VPT shifts towards other persons are larger than towards objects, we entered the Left/Right biases into an ANOVA with the within-subjects factor Location (Object/Human-left, Object/Human-right) and the between-subjects factor Group (object, human). A main effect of Location replicated the known Left/Right-biases towards person locations, $F(1,52)=23.328$, $p<.001$, $\eta_p^2=.310$, which was further qualified by an interaction with Group, $F(1,52)=7.636$, $p=.008$, $\eta_p^2=.128$, revealing larger shifts in the human than the object group (Figure 2D, see Figure S1CD for mental rotation curves).

Step-down analysis of the human group fully replicated the known pattern. Left/Right-shifts differed between Human-left and Human-right conditions, $t(27)=5.729$, $p<.001$, $d=1.08$, and each differed to the baseline No-human condition, $t(27)>2.449$, $p<.021$, $d=.457$. Recognition times again reflected the item’s angular difference to the participant, mean $\beta=1.46$, $t(27)=11.0$, $p<.001$, $d=2.09$, and to the other person, mean $\beta=.31$, $t(27)=5.70$, $p<.001$, $d=1.07$.

These shifts were virtually eliminated in the object group (Figure 2D). Left/Right biases in the Object-left, Object-right, and No-Human conditions did not differ from each other, $t(25)<1.722$, $p>.097$, $d<.338$. Moreover, recognition times only captured the item’s angular difference to the participant, mean $\beta=1.83$, $t(25)=16.6$, $p<.001$, $d=3.27$, but not to the lamp, mean $\beta=.08$, $t(25)=1.15$, $p=.262$, $d=.23$, and this mean beta-coefficient was smaller than in the Human group, $t(52)=2.72$, $p=.009$.

Explicit perspective taking increases bias towards other persons

People can make perceptual judgements from another's perspective if explicitly instructed [5,12]. Experiment 3 (n=52) therefore explicitly instructed half of participants to adopt the other persons' perspective (Explicit-VPT group) while giving no instructions to the other half (Implicit-VPT group), as in previous experiments. If our task truly indexes perspective taking (rather than biases in rotation direction for example), then such an explicit instruction should elicit the same, but more pronounced, biases towards the other persons, and be described by the same regression model.

Results fully supported our predictions. As before, Towards/Away-biases confirmed the mental rotation effect, in all conditions of both groups, $t(25)>5.168$, $p<.001$, $d>1.01$, for all. An ANOVA on Left/Right biases revealed the expected main effect of Person Location, $F(1,50)=120.419$, $p<.001$, $\eta_p^2=.707$, which interacted with Group, $F(1,50)=13.464$, $p=.001$, $\eta_p^2=.212$. Thus, as expected, the faster recognition of left- compared to right-oriented characters for persons sitting on the left, and vice versa for persons on the right, was even more pronounced in the Explicit-VPT than the Implicit-VPT group (Figure 3).

As before, our simple regression model described recognition times in terms of mental rotation from one's own and the other's viewpoint. Yet, while in the Implicit-VPT group recognition times again showed a stronger contribution of the item's angular difference to the participant, mean $\beta=1.31$, $t(25)=9.89$, $p<.001$, $d=1.93$, than the other person, mean $\beta=.40$, $t(25)=6.79$, $p<.001$, $d=1.34$, this difference was reduced in the Explicit-VPT group (Figure 3). It showed strong weightings of both the angular disparity to the participant, mean $\beta=.91$, $t(25)=6.182$, $p<.001$, $d=1.21$, and to the other person, mean $\beta=.84$, $t(25)=8.412$, $p<.001$, $d=.1.65$. Both coefficients differed between groups, $t(50)>2.017$, $p<.049$, $d>.56$.

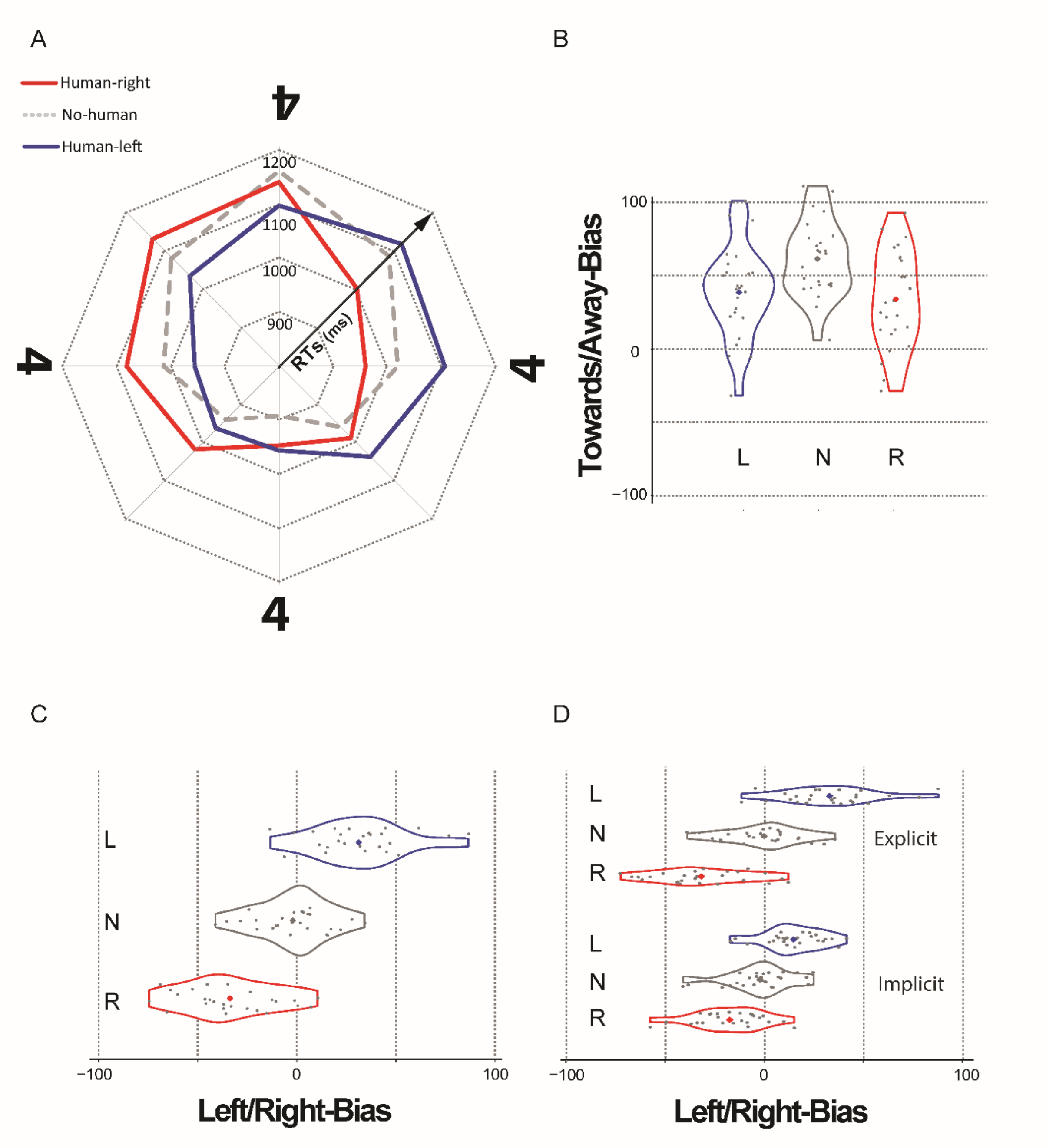

Figure 3. Results of Experiment 3: Explicit perspective-taking increases bias towards other persons. (A) Recognition times (ms) in the Explicit-VPT group to correctly classify items as canonical or mirror-inverted in each of the eight orientations, depending on whether the person was absent, was sitting on the left, or was sitting on the right. B) Violin charts showing the Towards/Away-bias when the person was not present (N), was on the right (R), or was on the left (L); means are indicated by diamond symbols. (C) Violin charts showing the Left/Right-bias when the person was absent (N), was on the right (R), or was on the left (L); means are indicated by diamond symbols. (D) Comparison with Implicit-VPT group: person location biases mental rotation curves in the Explicit-VPT group more strongly than in the Implicit-VPT group. Violin charts showing the Left/Right-biases in both groups when a human was on the right (R), was not present (N), or was on the left (L); means are indicated

by diamond symbols. See Figure S2 for the same data presented as line graphs, and Table S1 for error rate data.

Other's perspectives cause both facilitation and interference

Exploratory analyses with data pooled across experiments (1a, 1b, 2 human condition, 3 implict-VPT condition, see STAR methods for details) to increase power showed that the Left/Right shifts in the Human-left and Human-right condition reflected both facilitation for characters oriented towards the other persons, $t(120)=7.27$, $p<.001$, $d=.66$ and, to a lesser degree, interference, $t(120)=5.17$, $p=.001$, $d=.47$, when characters were oriented away, relative to the No-Human baseline condition.

Discussion

We tested whether humans have direct, (quasi-)perceptual access to the content of another's perspective that can stand in for own input. We show that the classic finding from mental rotation tasks – that it takes longer to recognise an item the more it has to be mentally rotated into its canonical orientation [18] – is disrupted by other persons in the scene. In this case, recognition times increase not only with an item's angular disparity to the participant but also to the other person, such that items oriented away from participants are recognised more rapidly if they are oriented towards this person (and even more slowly when oriented away from them). Recognition times therefore reflect an integration of one's own and the others' perspectives, either from parallel processes within each judgment or across them, when participants fluently switch between own and others' perspectives. The resulting biases had a large effect size, were sensitive to instructions to take the other's perspective, but decreased when the persons were replaced with mind-less objects, even when these objects had the same directionality and faced the items as the persons did. Results therefore show that the content of another's perspective is available in (quasi-) perceptual form, so that the characters could be mentally rotated from this perspective and are recognised more rapidly if they appear in their canonical "upright" orientation from this point of view.

While VPT has been proposed before to reflect perceptual simulations of others' viewing perspective [5,6] direct evidence has been lacking. Prior work has only shown interference on a conceptual and/or response level, leaving open whether participants simply represent that others see a scene *differently*, without representing their specific perceptual input [21-22]. Moreover, in these tasks, VPT was only observed when the other person was at least somewhat relevant to one's own task, leading to the proposal that while humans are endowed with a quick (and potentially automatic) mechanism that computes *what* others can see, deriving *how* they see it is under cognitive control [13, 15-17] and may require effortful mental rotation of one's own body into that of the other [5,12].

In contrast, the perceptual biases observed here reveal that humans can rely on others' visual perspective to drive own perceptual decision making. They therefore shown that VPT takes the form of a perceptual simulation that can drive subsequent processing like actual input, allowing it to be integrated into recent perceptual accounts of imagery and working memory, for which a similar reliance on (even early) visual representations has been demonstrated [see 7 for review]. Second, they challenge the notion that VPT2 is under cognitive control. Here, another's viewing perspective drove processing even (1) when the person stimulus was completely passive and task-irrelevant, (2) without requiring blocking person presence/location across trials or (3) asking participants to switch between self- and other-perspective, which can induce carry-over effects [11,23]. Moreover, (4) effects occurred rapidly, with an upper limit provided by the time it would take to mentally rotate the item oneself (about 100 ms for orientations to $90/270^0$), and involuntarily, even in trials (5) in which the other's perspective did not help but *interfere* with item recognition (because items were oriented even further away from them).

Together, these findings provide direct evidence that humans are endowed with a mechanism that allows them to rapidly and spontaneously derive *how* others see an object. The (inferred) view of the other person takes a quasi-perceptual form that can stand in for own sensory input. In this way, the content of another's perspective can feed directly into perceptual representations and can drive, in a bottom-up manner, the processes operating on them, without explicit control, as has been demonstrated for imagery and working memory [7].Such spontaneous perceptual simulations of others' viewing perspective could explain not only why better perspective takers are more empathetic [3,24], why people sometimes describe object locations from another's viewpoint, or why patients with hemispatial neglect sometimes report neglected items when imagined from a different perspective [25]. They may also provide novel insights into more sophisticated socio-cognitive abilities in humans, such as joint action and mentalizing, and their impairment in autism, which have been shown to be related to VPT [26].

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Author contributions

EW and PB designed the experiment with GG. EW programmed the study, prepared the stimuli and collected all data. EW and PB and GG analysed the data. EW, PB, GG wrote the manuscript.

Declaration of interests

The authors declare no competing interests.

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STAR★Methods

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Software and Algorithms		
GPower 3.1	Erdfelder, Faul, & Buchner, 1996	http://www.gpower.hhu.de/
Presentation software (Version 18.0)	Neurobehavioral Systems, Inc., Berkeley, CA,	https://www.neurobs.com/
R (version 3.5.1)	R Core Team, 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria	https://www.R-project.org/
RStudio (version 1.1.456)	RStudio Team, 2016. RStudio: Integrated Development for R. RStudio, Inc., Boston, MA	http://www.rstudio.com/
ggplot2	H. Wickham, 2009. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York	https://ggplot2.tidyverse.org/
Deposited Data		

Raw and analyzed data	This paper	osf.io/xzy5a https://osf.io/xzy5a/?view_only=3e0ae63189314572a4604ed060f813c7

CONTACT FOR REAGENT AND RESOURCE SHARING

Further information and requests for resources and reagents should be directed to and will be fulfilled by the Lead Contact, Patric Bach (patric.bach@plymouth.ac.uk).

EXPERIMENTAL MODEL AND SUBJECT DETAILS

Participants

203 (166 females) naive participants (42 in Experiment 1a, 37 in Replication Experiment 1b, 56 in Experiment 2, 68 in Experiment 3) were initially recruited via the University of Plymouth participation pool. All participants were adults (age range 18-50) and gave written informed consent according to the declaration of Helsinki. Approval was obtained from the University of Plymouth Ethics Committee. Participants received course credit as compensation. After exclusion (for criteria, see below), 34 participants (28 females; mean age: 22.8 years, range: 18-50) were considered for analysis in Experiment 1a, 33 in Experiment 1b (28 females, 21.7 years, age range: 19-50), 54 in Experiment 2 (42 Females; mean age: 20.07 years, age range: 18-34), and 52 in Experiment 3 (47 Females; mean age: 20.5 years, age range: 18-30).

METHOD DETAILS

Elimination criteria

In all experiments, erroneous responses were excluded from the analysis of recognition times (RTs), as well as trials with RTs longer than 2000ms, or shorter than 150ms. Participants with error rates in excess of 20% across all conditions were not considered for analysis (Experiment 1a, n=8; Experiment 1b, n=4; Experiment 2, n=2; Experiment 3, n=16).

Power analysis

Power analyses were conducted in G*Power (Version 3.1) [27], assuming a power of .80, using the sensitivity analysis function. We do not report theoretical power based on previously reported effect sizes as this neglects uncertainty around these effect size measurements [28-29]. Instead, we report effect sizes that can in principle be detected with our experimental parameters (i.e. given required power, participant numbers and type of test). These analyses were conducted for the crucial comparison of Left/Right-biases in the Human-left and Human-right conditions, which measures the extent that person presence biases mental rotation towards either 90^0 or 270^0.

For initial Experiment 1a, a final sample size of n= 34 provides .80 power to detect effect sizes in the predicted direction (one-sided) of at least Cohen's d=.43 and effects in either direction of Cohen's d=.49. As measured effect sizes from this experiment (and in additional piloting in our lab) robustly exceeded this criterion (d=.89), we replicated the study with similar sample sizes. For the replication Experiment 1b, the final sample size of n=33 allows us to detect effects in the predicted direction of at least Cohen's d=.44 and effects in either direction with Cohen's d=.50. Assuming that the object condition eliminates the effects in reported Experiment 1a and 1b, and that the between-participant standard deviation stays the same, anticipated effect sizes for the crucial between-groups comparison should again be larger (d=.89, when derived from effect sizes of Experiment 1, d=.85 when derived from Experiment 2). For Experiment 2, the final sample size of n=54 allows us to detect between-group differences of d=.69 (one-sided) and .77 (two-sided). Similarly, for Experiment 3, the final sample size of n=54 allows us to detect between-group differences of d=.69 (one-sided) and .79 (two-sided).

Experiment 1a and 1b - Apparatus, stimuli & procedure

All experiments were conducted in behavioural testing lab space of the University of Plymouth. The experiments were administered using Presentation® software (Version 18.0, Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com). Stimuli were presented on a 19” LED computer monitor (Resolution: 1900x1200; Refresh rate: 60Hz). Responses were made on a standard computer keyboard with UP, DOWN, and SPACE keys as active response keys. Red and green stickers were positioned on the DOWN and UP keys, respectively.

Participants sat upright facing the screen at a distance of approximately 60cm and were given written and verbal instructions. They were given examples of the rotated items that would appear on the screen and completed eight training trials that were identical to the main experiment (Figure 1). Each trial (total trials = 520) started with a fixation cross displayed for 400ms, followed by 300ms blank screen. The subsequent stimulus sequence included three frames, presented without inter-stimulus interval, creating the impression of apparent motion (Wertheimer, 1912). The first frame, measuring 33.4 by 23.5 degrees of visual angle, was presented for 800 ms. In 50% of the trials, it showed a view onto a corner of a square table in a grey room. In the other 50%, it showed a person sitting behind the same square table, gazing outwards at the participant. The person (either male or female) sat either on the left or right side of the table (12.5% of trials, each).

The second frame in the sequence was identical to the first for the No-human trials. In the trials with the person, (s)he now looked down towards the middle of the table. Then, after a random interval between 700ms and 1400ms, the third frame was presented. This was identical to frame 2, but now one of 64 possible items appeared on the table, at the location on the table the on-screen person was gazing at. This item was one of four alphanumeric characters (4, Z, P, or R), presented either in the canonical version or mirror-inverted about their vertical axis, in one of eight orientations (0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°, with 0° denoting the upright canonical orientation and angles increasing in a counter-clockwise fashion) relative to the participant. The characters always appeared in the same position on the table, half-way between the outward corner of the table and its centre, such that the persons to the left and right would gaze at the table from roughly 90° and 270°, respectively (perpendicular to the viewpoint of the participant, see Figure 1A inlay, Figure S3 for measurements of the scene setup), as at these angles the character's angular disparities from the participant and the other person were statistically independent across conditions. Character rotation occurred around the character's centre point.

Participants were asked to judge whether each character was presented in its canonical or mirror-inverted form. The third frame remained on the screen until a response was made to a maximum duration of 3500ms. Participants responded using their right hand by pressing the green key to indicate a canonical item and the red key to indicate a mirrored item. Response times were measured relative to item onset.

Following this task, participants were asked to report via free text any particular strategies they used for their judgements. Some reported that they noticed themselves sometimes taking the perspective of the other persons: Experiment 1a, *n*=5; Experiment 1b, *n*=5; Experiment 2, *n*=6; Experiment 3, *n*=4. No participants in the object condition reported taking the perspective of the lamp. All effects reported in the main text remain if these participants are removed from the analyses (see Robustness analyses below).

For a demonstration of the design (albeit with slightly different timing), please see the movie here: https://goo.gl/eAV1eg

Experiment 2 - Apparatus, stimuli & procedure

Participants completed a total number of 584 trials, following the same apparatus and procedure as in Experiment 1a, with the following exceptions. First, for half of the participants, the person in the picture was replaced with a lamp of similar height and orientation towards the character. The lamp was chosen as it possesses similar characteristics as other people, such as a clear front and back, and the potential to "look" in a certain direction on the table (see Figure 1B, lower panels). Second, the letter Z was removed from the item list because participants alerted us that it could be mistaken for an N when rotated 90 degrees. Third, the first (outward gaze towards the participant) frame (Figure 1A) was removed from the sequence. In Experiment 1a, the transition from Frame 1 (person gazing towards the participant) to Frame 2 (person gazing at the table) resulted in apparent motion and the impression of the other person directing attention to the item, which drew attention to the person, might signal internal states, and would therefore not be appropriate to the inanimate and mind-less lamp stimulus. In order to keep the trial duration consistent with that of the first experiment, the original second image in the sequence was presented for an additional 800ms. Fourth, to increase power for the crucial comparison between person/object on the left and right, the No-human trials were reduced to 33%. The remaining two thirds of trials were divided equally between the person/lamp appearing on the left and the right (33% each). To ensure that person and lamp trials were of equal variability, each participant in the Human group only saw only one of the two individuals (the male or the female), counterbalanced between participants.

Experiment 3 - Apparatus, stimuli & procedure

Participants completed a total number of 584 trials, following the same apparatus and procedure as in Experiment 2 (human condition), with the exception that half of the participants were simply instructed to take the perspective of the actors when they appeared on the screen, and to respond from their own perspective when there was no actor present. The exact instruction given was '*You will see some people appear on the screen. When this happens, I would like you to respond from their visual perspective. If there are no people visible on the screen, you should respond from your own perspective'.* The other half of participants did not receive any specific instructions to perspective-take. In fact, the presence of persons in some trials was not mentioned.

QUANTIFICATION AND STATISTICAL ANALYSIS

Data (pre-)processing and analysis were conducted in Microsoft Excel (2010), SPSS (version 23). Figures 2 and 3 were created using R (ggplot2). Power analyses were conducted in G*Power (Version 3.1; Erdfelder, Faul, & Buchner, 1996).

Dependent measures

Dependent measures were the recognition times (measured from item onset) for each character orientation (0°, 45°, 90°, 135°, 180°, 225°, 270°, 315), depending on condition (No-human, Human-left, Human-right). Analogous analyses of error rates were also conducted to rule out speed/accuracy trade-offs. In all experiments, error rates numerically followed the pattern of the main recognition times but did not show statistically reliable differences (Table S1).

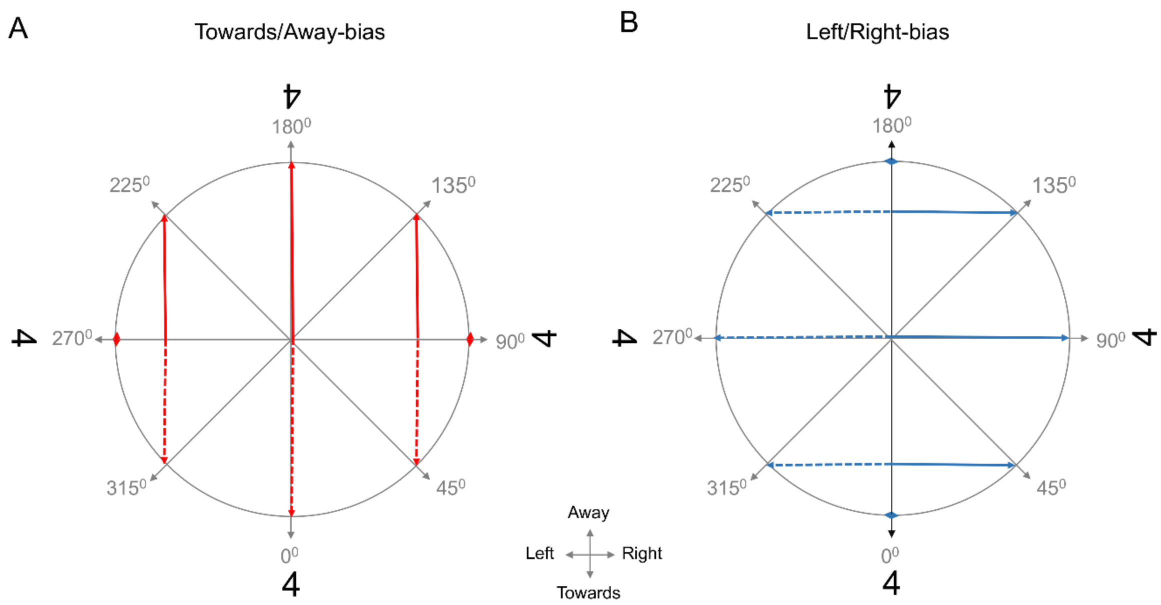

Figure 4. The contribution of each character orientation to the summary measures Towards/Away-bias (A) and Left/Right-bias (B). Each character's contribution to the Towards/Away-biases and Left/Right-biases are defined by the negative of the cosine and the sine of the character rotation angle, respectively. The red arrows show the positive (filled arrows) and negative (dotted arrows) contributions of each character orientation to the Towards/Away-bias. The blue arrows show the positive (filled arrows) and negative (dotted arrows) contributions to the Left/Right-bias.

Toward/Away-bias and Left/Right-bias

To quantify the recognition times when the characters either faced the participant (i.e. was seen in its canonical orientation from the perspective of the participant) or the other person in the scenes, we derived two analogous and statistically independent summary measures. The first summary measure (Toward/Away-bias) indexes to what extent characters were recognized faster the more they were facing towards the participant (0°) rather than away from them (180°), separately for each participant and each condition (No-human, Human-left, Human-right). This measure therefore quantifies the mental rotation effect [18]. The second summary measure (Left/Right-bias) indexes how much faster characters were recognized when oriented towards the left (270°) rather than right (90°), or vice versa.

The contribution of each character orientation to the two summary measures is derived by treating each participant's recognition time for this character orientation as a vector in a coordinate system, with the recognition time providing the distance from the origin and the rotation angle the polar angle. A character orientation's contribution to the Toward/Away-bias is then derived simply from the recognition times multiplied with the negative of the cosine of the orientation angle. As a result, characters contribute negatively the more they face the participant (315°, 0°, 45°; Figure 3A, red filled arrows) and positively they more they are oriented away from them (225°, 180°, 135°; Figure 3A, red dotted arrows). Similarly, the contribution of a character's orientation to the Left/Right-bias was calculated as the recognition time multiplied with the sine of the orientation angle. Character orientations contribute positively the more they face to the right (45°, 90°, 135°; Figure 3B, blue dotted arrows) and negatively the more they face to the left (225°, 270°, 315°; Figure 3B, blue filled arrows). This procedure effectively maps the changes evident in the radar plots for each angle onto two orthogonal and statistically independent summary measures, so that they can be compared across conditions (either within- or between-participant), without accruing alpha inflation due to multiple testing, which would result if each of the eight angles were compared separately.

By averaging these values, separately for each summary measure, participant and condition (No-human, Human-left, Human-right), we are able to calculate, first, whether characters were recognized faster the more they appear in the canonical orientation to the participant (negative values on the Toward/Away-bias) compared to when they are oriented away (positive values), reflecting the expected mental rotation effect. Similarly, they allowed us to calculate to what extent characters were recognized faster the more they are oriented leftwards and would appear in their canonical orientation to a person sitting to the left (positive values on the Left/Right-bias) rather than rightwards, appearing in their canonical orientation to a person sitting on the right (negative values). We were then able to determine if this left/right bias changed depending on whether another person was presented in the scenes and on whether the person was on the left or on the right.

The crucial comparison is the difference between the Left/Right-biases in the Human-left and Human-right conditions, but additional comparisons of interest are also reported. Note that the direct comparison of the Human-left and Human-right conditions is statistically identical to the comparison of how much person presence shifts mental rotation performance in the Human-left and Human-right conditions relative to the No-Human baseline (i.e. how much person presence shifts recognition times away from 0^0 towards either 90^0 or 270^0), as this would involve subtracting the same baseline value from each of the two conditions for each participant, and would therefore not affect the absolute difference between them. In Experiment 1a and 1b, differences between these conditions were assessed with repeated measures t-tests. Effect sizes were measured in Cohen's *d*. In Experiment 2, a mixed-factors ANOVA with the within-subjects factor Location (left, right) and between-subjects factor

Group (human, object) was used to assess whether the difference in Left/Right-biases towards a person on the left or right was larger than the difference in perceptual shifts towards an inanimate object (a lamp) in the same position. In Experiment 3, the same ANOVA model was used to whether the difference in Left/Right-biases towards a person on the left or right increased when participants were explicitly instructed to take the other person's perspective compared to when they received no instruction, as in the previous experiments.

Distinguishing between facilitation and interference

Additional analyses were conducted on the pooled data across experiments (Exp. 1a, Exp. 1b, Human condition of Experiment 2) to verify whether the measured Left/Right-biases towards person locations reflect only facilitation (i.e. faster recognition of items oriented towards another person) or interference as well (slower recognition of items oriented away from the other person). To this end, we used the same logic as for the overall perceptual shifts and again scaled average recognition times by the sine of each character orientation, but separately for the trials in which the items were facing towards the other person (e.g. for a person on the right: 45^0, 90^0, 135^0) and away from the other person (e.g. 315^0, 270^0, 225^0), separately for the Human-Left and Human-Right conditions, across all participants of the three experiments to increase power (Experiment 1a, 1b, human group of Experiment 2, implicit group of Experiment 3). We were then able to separately assess, with paired t-tests, whether recognition times were generally slower than would be expected from the baseline No-human condition for items facing away from the other person (i.e. measuring interference), and whether they were faster than expected when facing towards the other person (measuring facilitation).

Across-participant regression analyses

In prior work, the mental rotation effect is sometimes characterised in terms of separate linear regressions of an items' recognition time to its angular disparity relative to the participant, for each participant separately [18]. The results reveal linear increases with increasing angular disparity for the large majority of participants. Here, we used this analysis model to test whether an item's recognition times can be described, on a single participant basis, as a linear increase of the character's angular disparity *both* to the participant and to the other person. To this end, we entered each participant's item mean recognition times for each character orientation in the Human-left and Human-right condition as dependent variable in a multiple regression, with the item's angular disparity to the participant and to the other person as two statistically independent predictors. This analysis provides regression coefficients for both predictors – angular disparity to participant and other person – for each participant separately. We report mean across-participant regression coefficients for each of these two predictors and compare them with t-tests against zero.

The fit of model and observed data can be seen in Figure S2, separately for the aggregated data across all experiments in which VPT was induced implicitly in the top row (Exp. 1a, 1b, Exp. 2 human group, Exp. 3 Implicit-VPT group) and when it was induced explicitly in the bottom row (Exp. 3). To increase power, the data of the Human-right condition was "flipped" and collapsed onto the data for the (mirror-symmetrical) Human-left condition (so that recognition times for 270^0 when a person sitting on the left map onto 90^0 for a person sitting on the right). The left panels (A, D) show the data predicted from the average across-participant regression coefficients and intercepts, for the No-Human "baseline" condition, and the Human-left condition. The middle panels (B, E) show the observed data for the No-human condition and the Human-left condition. Finally, the right panels (C, F) show the residuals when *only* the expected mental rotation function from the participant's own perspective is regressed out. As can be seen, these residuals show a mental rotation function from the perspective of the other person (sitting at 270^0), showing graphically that, in the Human-left and Human-right conditions, an item's recognition times across angles can be decomposed into mental rotation functions from one's own and the other person's perspective.

Robustness analyses

We confirmed that our effects did not depend on specific (groups of) participants. We first verified that our analysis still holds when all participants were excluded that explicitly reported noticing taking the perspective of the other individuals in the scene. This was the case, without substantially reducing overall effect sizes (Experiment 1a, excluded n=4, $t(29)=5.052$, $p<.001$, $d=.92$; Experiment 1b, excluded n=3, $t(29)=4.316$, $p<.001$, $d=.79$; Experiment 2, human group, n=5, $t(22)=5.167$, $p<.001$, $d=1.08$; no participants reported VPT in Experiment 2, object group; Experiment 3, implicit group, excluded n=4, $t(21)=6.634$, $p<.001$, $d=1.41$).

Second, we verified that our effects are not over-inflated due to some participants being older than usual (>35 years, Experiment 1a, $n=5$; Experiment 1b, $n=2$; Experiment 2, $n=0$; Experiment 3, $n=0$). While there was a weak correlation with the difference in Left/Right-bias between the Human-left and Human-right condition and participant age across all participants ($r=.294$, $p=.001$), re-running these tests with older participants excluded revealed overall identical effect sizes. Indeed, when we exclude all participants older than 35, the overall effect size in Experiment 1a decreases (from $d=.89$. to $d=.80$) but increases in Experiment 1b (from $d=.85$ to $d=.94$).

DATA AND SOFTWARE AVAILABILITY

All data and main analyses files for these articles are accessible via OSF via this link:

https://osf.io/xzy5a/?view_only=3e0ae63189314572a4604ed060f813c7.

Supplemental Information titles and legends.

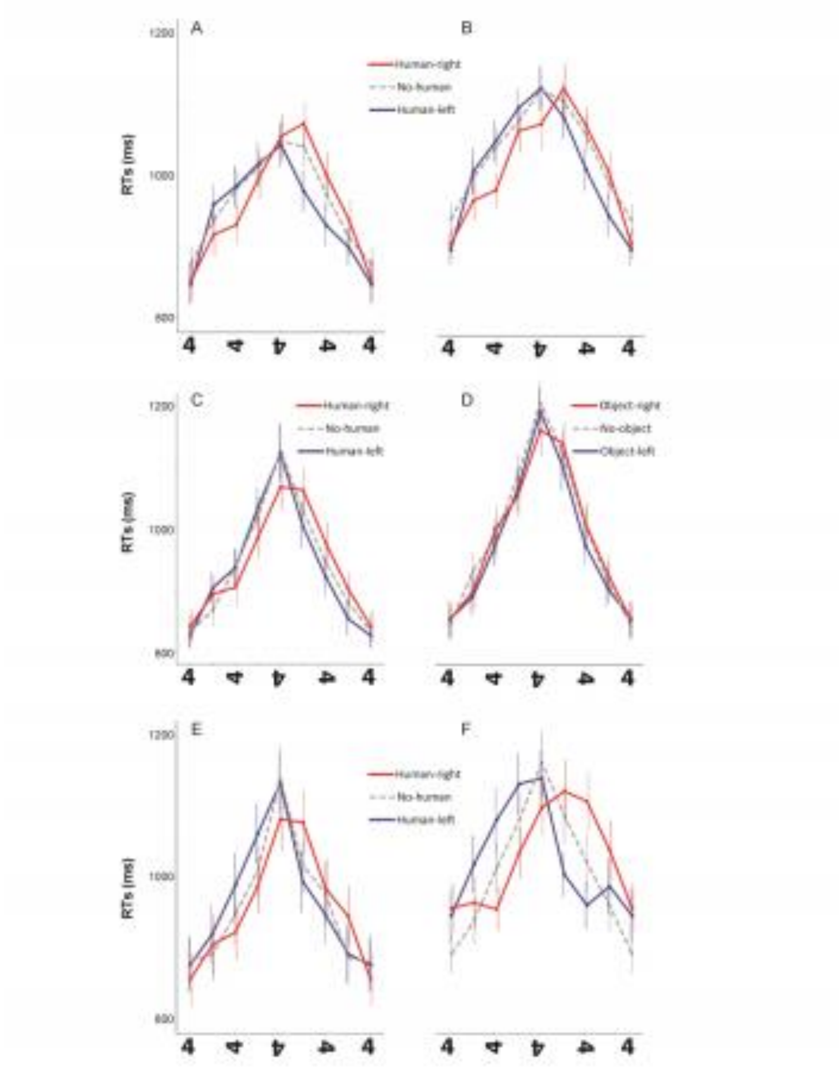

***Figure S1*. Results of Experiments 1a, 1b, 2 and 3 in line graph form.** Relates to Figure 2 (Person location systematically biases mental rotation curves) and Figure 3 (**Explicit perspective-taking increases Left/Right-bias)**. (A) Results of Experiment 1a. (B) Results of Experiment 1b. (C) Results of Experiment 2, Human Group. (D) Results of Experiment 2, Object group. (E) Results of Experiment 3, Implicit-VPT group. (F) Results of Experiment 3, Explicit-VPT group. In each plot, data points show recognition times (RTs) for all eight character orientations when the other person was not present (No-Human, grey lines), was on the right (Human-Right, red lines), or was on the left (Human-Left, blue lines). Note that, following symmetry conventions in these plots in the literature, the data points for 0^0 angular disparity are identical with the data points for 360^0 angular disparity.

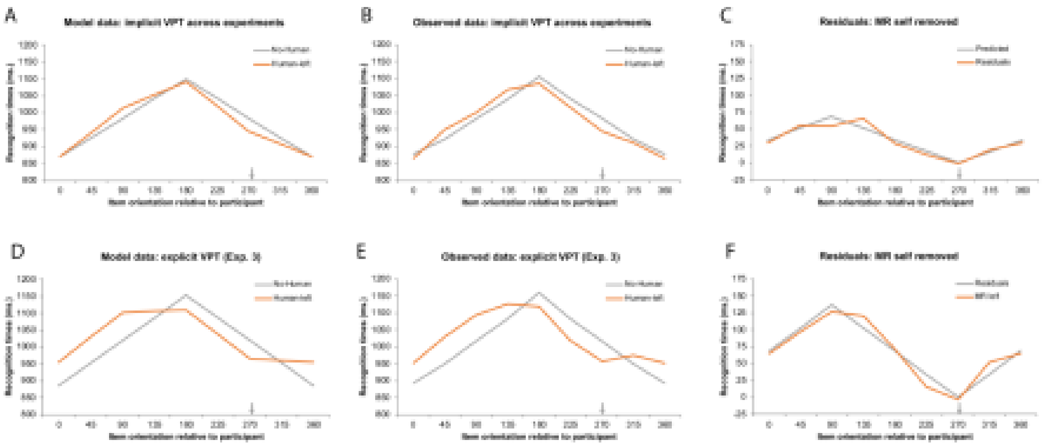

***Figure S2*. Fit of regression model and observed data.** Relates to Figure 2 and 3. The top panels show the aggregated data across all experiments in which VPT was induced implicitly (Exp. 1a, 1b, Exp. 2 human group, Exp. 3 Implicit-VPT group). The bottom row shows the data when VPT was induced explicitly (Exp. 3). For all panels, the data of the Human-right condition was “flipped” and collapsed onto the data for the (mirror-symmetrical) Human-left condition, with the small arrow indicating the viewpoint of the other person at 270^0. The left panels (A, D) show the data predicted from the average across-participant regression coefficients and intercepts, for the No-Human “baseline” condition, and the Human-left condition. The middle panels (B, E) show the observed data for the No-human condition and the Human-left condition. The right panels (C, F) show the residuals when only the expected mental rotation function from the participant’s own perspective is regressed out, leaving a mental rotation function centred on the other person’s perspective (270^0).

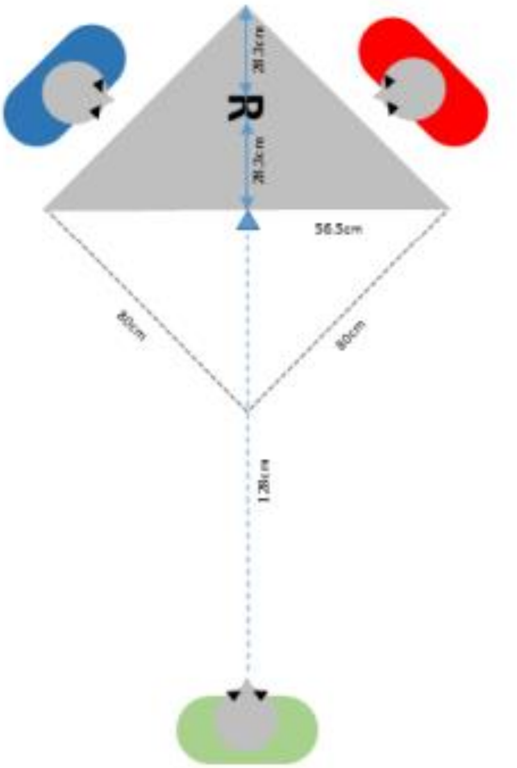

***Figure S3*. Scene Dimensions.** Measurements for the setup of table, person locations (red, blue) and observer/camera position (green) from which all experimental stimuli were derived. Relates to Figure 1.

Table S1. Means (M) and Standard Deviations (SD) for the Left/Right- and Towards/Away-biases in Error rates in Experiment 1a, 1b, Experiment 2, and Experiment 3. Relates to Figure 2 and Figure 3 and Figure S1. Forward/Away and Left/Right-biases were calculated analogously as for the recognition times. **p*<.05. **p<01, ****p*<.005.

	Y-Axis			X-Axis		
Experiment	Human-Left M(SD)	Human-Right M(SD)	No-human M(SD)	Human-Left M(SD)	Human-Right M(SD)	No-human M(SD)
1a	.014 (.025)**	.011(.017)***	.019(.016)***	.002(018)	-.004(018)	.002(015)
1b	.020(.020)***	.015(.023)***	.014(.014)***	.006(019)	-.002(017)	-.002(012)
2 Human	.021(.015)***	.024(.02)***	.027(.025)***	.001(012)	-.003(018)	-.001(015)
2 Object	.027(.025)***	.027(.026)***	.023(.025)***	-.001(018)	-.001(016)	-.002(013)
3 Implicit	.019(.015)***	.02(.021)***	.017(.017)***	.005(.011)*	-.002(.016)	.001(.017)
3 Explicit	.016(.024)***	.012(.022)*	.021(.024)***	.015(.022)***	-.008(.023)	-.004(.012)