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Reaction time profiles of adults' action prediction reveal two mindreading systems

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ABSTRACT

Human beings are able to quickly step into others' shoes to predict peoples' actions. There is little consensus over how this cognitive feat might be accomplished. We tested the hypotheses that an efficient, but inflexible, mindreading system gives rise to appropriate reaction time facilitation in a standard unexpected transfer task, but not in a task involving an identity component. We created a new behavioural paradigm where adults had to quickly select whether an actor would reach, or not reach, for an object based on the actor's false belief about the object's location. By manipulating the type of object we compared participants' responding behaviour when they did and did not have to take the actor's perspective into account. While the overall accuracy reflected a high level of flexible belief reasoning across both tasks, the pattern of response times across conditions revealed a limit in the processing scope of an efficient mindreading system. Thus, we show, for the first time, that there are indeed different profiles of reaction times for object-location scenarios and for object-identity scenarios. The results elevate growing evidence that adult humans have not one, but two mindreading systems for dealing with mental states that underlie action.

1. Introduction

Decades of research on standard false-belief tasks requiring direct verbal reasoning, indicate that theory-of-mind (TOM, also referred to as mindreading) emerges in humans from about 4 years of age (Wellman, Cross, & Watson, 2001). Younger children fail to explicitly reason about others' minds in tasks that present a disparity between the child and the target agent. For example, in the "unexpected transfer" task (e.g., Maxi-chocolate or Sally-Anne test; Baron-Cohen, Leslie, & Frith, 1985; Wimmer & Perner, 1983) a character sees a desirable object in one location before leaving the scene. During the character's absence another character switches the item to a different location. When the protagonist returns, 3-year-olds incorrectly predict that the character will look in the new location rather than in the place they left it. At this age, children also fail the "unexpected contents" test (e.g., Perner, Leekam, & Wimmer, 1987). In this task children are asked what they think is inside a container that looks like it should hold one type of content (e.g., a Smarties tube). It is then revealed to them that the box contains, for example, paperclips instead of Smarties. Three-year-olds incorrectly predict that a naïve agent would guess the true contents of the container, whereas most 4–5-year-olds grasp that the newcomer's belief would be incongruent with reality. For these older children TOM is conceptually unified: they appreciate that beliefs can be true or false and that people's representations of the world come from a specific, subjective viewpoint (Rakoczy, 2015; Rakoczy, Bergfeld, Schwarz, & Fizke, 2015).

There is considerable evidence that belief reasoning is cognitively demanding; it requires input from executive resources (e.g., Apperly, Back, Samson, & France, 2008; McKinnon & Moscovitch, 2007; Rowe, Bullock, Polkey, & Morris, 2001) and also succumbs to egocentric biases (Birch & Bloom, 2007; Epley, Keysar, Van Boven, & Gilovich, 2004; Keysar, Barr, Balin, & Brauner, 2000; Keysar, Lin, & Barr, 2003). The classical view is that advances in language, executive function and participation in complex social interactions help children learn about subjective mental representations (Low & Perner, 2012; Perner, 1991; Wellman, 2014). However, indirect response procedures (e.g., measuring anticipatory or expectant looking) appear to challenge the idea that TOM undergoes significant conceptual change over the preschool years. For example, 3-year-olds show correct eye gaze anticipations in false-belief tasks despite giving incorrect (reality-based) verbal predictions (e.g., Clements & Perner, 1994; Low, 2010; Wang, Low, Jing, & Qinghua, 2012). Young children in small-scale societies also show correct gaze anticipations whilst giving incorrect verbal

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predictions in standard object-location false-belief tasks (e.g., Wang, Hadi, & Low, 2015). More dramatically, infants as young as 13 months of age show some sensitivity to others' mistaken belief-based actions: infants look longer when they observe other people searching in locations that are inconsistent with their false belief of an object's whereabouts (for a review see Sodian, 2016). If TOM is cognitively effortful, then why do non-verbal studies reveal impressive performances from infants?

Adding to the mystery, research with adults indicates that mindreading is sometimes automatic and sometimes not automatic. Schneider, Nott, and Dux (2014) found that a character's false belief affected participants' behaviour even though it had no bearing on their task. They asked one group of participants to track a character's belief and another to track the location of a ball; both looked longer at an empty box in which the character falsely believed a ball to be, compared to a true belief condition in which the character's belief and ball location were consistent. Task-irrelevant tracking of a character's belief was also revealed in a Kovács, Téglás, and Endress' (2010) reaction time study. Adult participants were asked to press a button if they detected an object on removal of an occluder. As expected, reaction times were facilitated by their own belief that the object would be present, but more importantly, they were also speeded when a passively observing character believed that the ball would be present, despite the participant having witnessed the ball leave the scene. Van Der Wel, Sebanz, and Knoblich (2014) also found that adults automatically tracked a bystander's belief about the location of a ball even though there was no reason to do so. These findings, along with those from the visual perspective-taking domain (e.g., Qureshi, Apperly, & Samson, 2010; Samson, Apperly, Braithwaite, Andrews, & Scott, 2010) indicate that mindreading may be in some respects automatic. However, there is also evidence to show that mindreading is not a compulsory, stimulus-driven mechanism (Apperly, 2011). Apperly, Riggs, Simpson, Chiavarino, and Samson (2006) presented participants with a typical unexpected transfer false-belief scenario and instructed them to track the location of a ball. They found that, despite a scenario that was conducive to mindreading, people were slower to react to a question regarding the character's false belief than to a reality probe. If participants undertook automatic mindreading they would be equally as fast. Subsequent work of this nature has reinforced the idea that although not automatic, mindreading can occur spontaneously, given the requisite context, cues and motivation (Back & Apperly, 2010; Biervoye, Dricot, Ivanoiu, & Samson, 2016; Cohen & German, 2009). As adult humans, we recognize from our everyday experiences that we possess the capacity to make snap judgments about, *and* slowly cogitate over someone's behaviour. The challenge is to determine the cognitive components that underlie these distinct mindreading abilities.

1.1. Rich versus lean

There have been attempts to reconcile the contradictory findings in developmental and adult TOM research. Advocates of the early mindreading account (e.g., Carruthers, 2013, 2015, 2016) claim that infants have an abstract (possibly innate) psychological reasoning system and that standard TOM tasks, relying on direct measures, underestimate children's abstract mentalistic competencies. Essentially, 3-year-olds fail where infants succeed because they lack the necessary language, knowledge and executive function to respond explicitly in standard belief testing. Carruthers describes a high-level, one-system account in which infants start out with core mental-state concepts (e.g., thinks, likes) and that they can attribute meta-representational states to others (e.g., "Daddy thinks there is a toy in my box") without an explicit understanding of what is true and false. Mastery of these concepts occurs in time, but there is no change to the fundamental architecture of the representational mechanism from infant to adult.

At the other extreme, infant success is construed as the result of low-level processes. Perner and Ruffman (2005) point to infants' sensitivity to behaviour rules; they rely on past experiences to predict an agent's action (e.g., people tend to look for things in the last place they saw them). Following a systematic assessment of infant false-belief studies, Ruffman (2014) concludes that infant performances can be explained by (domain general) statistical learning combined with an innate or early developing curiosity for eyes, faces and biological movement. The transition to adult-like mind reasoning is facilitated by language development and vital inputs from the social environment. Another non-mentalistic account interprets infant success in terms of low-level novelty wherein looking behaviour reflects the extent to which the perceived stimuli are novel with respect to previously encoded events (e.g., Heyes, 2014). These interpretations strongly oppose the idea of a modular, representational mechanism for infant mindreading. Theoretically, in infants and non-human animals there is always room for a non-TOM explanation wherein there is no way to empirically test between behaviour-reading and mind-reading (termed 'the logical problem' by Lurz, 2011). Mental states come with behavioural correlates, so how can we be sure that infants are using mental state concepts rather than learnt associations when predicting others' behaviours (Ruffman, Taumoepeau, & Perkins, 2012)? The problem with such a viewpoint is that it can explain findings, but not necessarily predict them.

1.2. 2-Systems

Confronted with such an impasse, Apperly and Butterfill (2009) offer a promising two-systems solution that features both 'lower level' (System 1) and 'higher level' (System 2) processing. According to this account, human adults have an efficient as well as a flexible mindreading system. System 2 supports direct verbal predictions and abstract mental state reasoning, and develops from age 4 years. However, the flexibility of such a system is cognitively costly as it makes deep and lasting demands on executive function resources. System 1 (available in infants, children and adults) guides indirect responses in fast-moving situations (e.g., eye gaze in certain tasks), and imposes relatively fewer demands on general cognitive resources. This lower level system operates outside awareness and may interact with the flexible system in a circumscribed manner (Apperly, 2011; Low, 2010; Ruffman, Garnham, Import, & Connolly, 2001). System 1 uses a minimal model of mind that involves tracking *belief-like* states, called registrations – relational attitudes whose contents can be picked out by simple relationships between agents, objects and locations. By contrast, System 2 guides action deliberations and justifications. It uses a canonical model of mind where mental states like belief are treated as propositional attitudes that are essentially subjective in nature (Butterfill & Apperly, 2013; Low, Apperly, Butterfill, & Rakoczy, 2016). The limited processing scope of System 1 precludes representation of belief as such but is sufficient to enable infants to pass certain false-belief tasks. Crucially, whilst adults have full-blown belief reasoning capabilities, they also have at their disposal, an efficient system enabling fast paced anticipations and responses pertaining to others' actions. The apparent contradictions in adult studies are explained by the fact that mindreading is governed by circumstances which determine which system is utilized.

Low and Watts (2013) tested the 2-Systems account by investigating whether the efficient mindreading system, as compared to the flexible system, would be subject to certain signature limits. A signature limit of a system is a pattern of behaviour that the system exhibits which is both defective, given what the system is set up to handle, and peculiar to that system. Identifying signature limits can therefore provide evidence concerning which systems underlie performance on different tasks and in different types of subjects (e.g., Carey, 2009). Low and Watts reasoned that, without propositional attitude representation, System 1 would fail to take into consideration the particular way in which a single object is construed from different perspectives. They hypothesized that children and adults would exhibit correct anticipatory looking in a *standard* unexpected transfer task, but not in a task that involved inducing a false belief about the *identity* of an object. In the familiarization trials of their identity false-belief task, participants saw two boxes in front of a screen in which two windows had been cut. Behind the screen the participant could see an agent with full visual access to the boxes, one of which contained a blue object, the other a red object. When the lights around the windows flashed the agent always reached through one of them to retrieve a blue object (colour preference was counterbalanced). The test trial involved a single object, a red-blue dog-robot. On the initial move from one box to another, the red side was visible to the participant and the blue side to the agent. When it reached the box it spun around showing its dual aspect to the participant only. It then returned to the left box with its blue side facing the participant. If participants can efficiently track belief as such, they should infer that the agent would believe there were two objects (when in fact there was only one object) and that a separate blue dog was still in the right box. All age groups (3-, 4-year-olds and adults) showed incorrect gaze anticipation (looking first and longer at the full box containing the object itself). The same participants also completed a standard object-location false-belief task: individuals across age groups showed correct gaze anticipants (looking first and longer at the empty box). Participants' direct reasoning was not subject to signature limits – the accuracy of participants' verbal predictions increased with age (showing above chance performance from age 4 years onwards). Low and Watts' pattern of findings have been replicated in studies testing diverse ages, populations and paradigms (e.g., Fizke, Butterfill, & Rakoczy, 2013; Low, Drummond, Walmsley, & Wang, 2014; Mozuraitis, Chambers, & Daneman, 2015).

There are challenges to the theorizing and empirical findings of Apperly, Butterfill, Low and their colleagues. Scott and Baillargeon (2009) claimed that 18-month-olds could attribute belief about identity. However, this task involved two toy penguins, one that could be pulled apart (2-piece penguin) and another that could not (1-piece penguin). The infants watched as an agent placed a key in the bottom half of the 2-piece penguin and then reassembled it. The two penguins now looked identical. In the test trials, when the agent was absent, an experimenter stacked the 2-piece penguin and placed it under a transparent box. She then placed an opaque box over the 1-piece toy. When the agent came back with a key the infants looked reliably longer when the agent chose the transparent box. From a mentalist viewpoint this is because the infant was surprised that an agent would reach for the transparent box if they falsely believed the 2-piece penguin to be the 1-piece penguin. But how substantiated is this claim? After all, the presence of two objects suggests that infants are simply reasoning about types of objects, irrespective of identity (Butterfill & Apperly, 2013; Low et al., 2016). Moreover, in the familiarization phase the agent never orients towards the intact penguin, so the infants' surprise is perhaps due to the first occurrence of this event in the false-belief task (Heyes, 2014; Ruffman, 2014). Nonetheless, Scott, Richman, and Baillargeon (2015) maintain that infants' psychological reasoning system is conceptually rich and abstract, and report evidence that 18-month-olds can even reason about one person's intention to implant in another person a false belief about object identity.

Currently, there are several limitations in what is known about the development of belief understanding. The problem is that, whilst measuring indirect behaviour has led to impressive advances in the TOM field, looking time responses alone cannot definitively answer the question of whether efficient belief-tracking is underpinned by a canonical understanding of belief, statistical learning or a minimal understanding of belief-like states (Fizke et al., 2013; Schneider & Low, 2016; Schneider et al., 2014). Whereas looking time signposts competency, it does not illuminate the underlying cognitive processes (Haith, 1998). One of the downsides of using a method originally designed to answer perceptual and sensory questions is that researchers must be prepared to defend their high level cognitive interpretations against perceptual ones (Heyes, 2014). Moreover, debates about the cognitive processes of belief reasoning focus on children's task performances without consideration of the mature mindreading system those children grow into (Apperly, 2011). The contradictory findings of adults' automatic as well as non-automatic mindreading expose a gap in our understanding; deeper insight into how humans manage the dual and contradictory demands of efficient as well as flexible mindreading can only be gained if we study mental state reasoning in adults as well as infants. As such, we were motivated to design a simple task for adults, that was conceptually related to developmental procedures, with the potential to uncover the component processes underlying TOM. Extending Low and Watts (2013), the current study seeks to distinguish between competing TOM accounts using an action-prediction paradigm devised by Southgate and Vernetti (2014).

1.3. Action-prediction

Southgate and Vernetti (2014) investigated infants' and adults' sensitivity to the relationship between an agent's beliefs and subsequent actions. In their unexpected transfer scenario, 6-month-olds were shown familiarization trials in which an agent either reaches for a box into which a ball has jumped, or does not reach for a box after a ball has left the scene. In the experimental phase, participants passively observed multiple video presentations of two conditions in which a false belief was induced in a female agent; in half of the test trials, the participant, but not the agent, saw an absent ball return to the box, while in the other half she saw the present ball leave the box. Notably, anticipation was not measured by looking behaviour but by motor cortex activity. They exploited the finding that the motor cortex is recruited, not only when one is observing another's action, but also when one is generating a prediction of that action (e.g., Cross, Stadler, Parkinson, Schütz-Bosbach, & Prinz, 2013; Kilner, Vargas, Duval, Blakemore, & Sirigu, 2004; Southgate, Johnson, El Karoui, & Csibra, 2010). In their electroencephalography study they used a decrease in alpha activity over the sensorimotor cortex as a proxy for motor activation. In doing so, the presence, or not, of alpha suppression informed whether a participant anticipated an agent's movement, based on their appreciation of the agent's 'belief'. The authors found that both adult and infant participants correctly predicted a reaching motion from the actor when she falsely believed the ball was in the box, but not in the opposing condition in which the ball entered the box without the agent's awareness.

According to the early mindreading account, action prediction requires that a participant represents both the agent's goal (e.g., she desires a ball from the box) and the agent's belief about this goal (she believes it's in the box). If this is the case then Southgate and Vernetti's (2014) study indicates that infants showed sophisticated mindreading capabilities. An alternative interpretation is that the infants learned, over successive trials, to associate outcomes (reaching or no reaching) with prior events occurring in the video sequences. The authors rejected this interpretation; they reasoned that if the infants were learning over multiple trials, their anticipatory motor cortex activation (for reaching trials) would have gradually strengthened. Instead, they found that the activity was greatest over the first few trials. According to the 2-Systems account, it is infants' efficient ability to track the actor's belief-like state, or registration, that supports their accurate action-predictions in this standard unexpected transfer task. According to this viewpoint, infants would fail to accurately predict the agent's reaching behaviour if the same procedure involved an object that gave rise to different experiences depending on perspective.

1.4. The current work

The evidence for the extent to which representing beliefs about an object's identity is a signature limit of the efficient mindreading system is mixed. This is partly due to the current emphasis on infant studies, and the focus upon looking time data. Our goal was to provide new and converging *behavioural* data from an *adult* sample to tease apart the 2-System account from the early mindreading account. To achieve this our research preserved the rationale of Southgate and Vernetti's (2014) action prediction paradigm but transformed it into a response time study. The central feature of this modified procedure was an 'identity' component that allowed us to investigate the existence of signature limits on adults' efficient belief reasoning when differing perspectives lead to different experiences of the same object.

Our specific aim was to determine whether adults would react more quickly in situations when they anticipated a particular response from an actor, compared to when they anticipated no response. We devised a simple procedure whereby participants had to select whether they thought someone with a false belief would or would not reach for a box to retrieve a desired or undesired object. To aid understanding, we describe our experimental design and hypotheses with an assumption that the actor desires blue objects, but does not desire red objects (the actor's colour preference was counterbalanced in the experiment). Of particular interest was how the type of object used would affect response times. To determine this we compared adults' performances in two different action prediction tasks. In the standard unexpected transfer task (henceforth referred to as the 'Location' task) the object seen by the participant and actor was either a fully blue or a fully red ball. In a second task (termed the 'Identity' task) we used an object specifically designed to investigate the identity component outlined above; this was a single, dual aspect dog-robot, which appeared blue if viewed from one side and red if viewed from the other side (see Fig. 1). Of our two dependent variables, error rates (gauging accuracy) served as a measure of System 2's flexible mindreading, whilst response times reflected the extent to which mindreading is affected by the efficient processing of System 1.

Our study exploits the idea that deployment of motor preparatory mechanisms facilitates the processing of actions (Thillay et al., 2016). The anticipatory activity exhibited by motor cortical neurons translates to a preparatory state in which the motor cortex is primed for optimal processing (Confais, Kilavik, Ponce-Alvarez, & Riehle, 2012). Thus, our justification for measuring reaction times derives from the robust evidence that motor activity occurs *prior* to observing a movement (Kilner et al., 2004) and that by pre-activating cortical areas, motor preparation mechanisms will lead to speeded response times (Bidet-Caulet et al., 2012). To maximize this effect, participants' responses had to correspond to the right-handed reaching movement of the agent; participants were required to use their right hand only to reach for a response key in every trial.

We tested two hypotheses based on the 2-Systems account. Hypothesis 1 was that, in the Location task, participants would be fastest to respond when the actor falsely believed that a desired (blue) object was in the box (the A_D+ condition). We refer to this as the 'Location Hypothesis'. By contrast, Hypothesis 2 was that participants in an Identity task would be fastest to respond when the actor falsely believed that an *undesired* (red) object was in the box (the A_U+ condition). Henceforth, this will be referred to as the 'Identity Hypothesis'. These predictions are compared with those of an early mindreading account in Fig. 2. According to a 2-Systems account, in the A_D+ condition of the Location task (Fig. 2a), a participant's System 1 tracks the actor's registration (or belief-like state) that the preferred ball is in the box, even though it is no longer there. Motor cortex activation is triggered because the actor's goal-directed action is to retrieve it; this then facilitates the fastest responding in the A_D+ condition. An early mindreading interpretation (Fig. 2b) is that motor cortex activity is generated by a single, possibly innate, mindreading system that tracks mental states – in this case, the actor's false belief that the desired ball is present. Both mindreading accounts would predict fastest responding in the A_D+ condition of the Location task.

In the A_D+ condition of the Identity task, the accounts offer contradictory predictions. According to the 2-Systems view (Fig. 2c), there is no anticipatory motor cortex activation as System 1 erroneously tracks that the actor last registered an unwanted (red) object in the box. The signature limit is revealed as a failure to take into account the *way* in which the actor perceives the object. An early mindreading account (Fig. 2d) does predict response facilitation in the A_D+ condition because of the sophisticated representational capacities of the single-system, which tracks the agent's false belief that the desired (blue) object is the box. An early mindreading account, but not a 2-Systems account, would predict fastest responding in this condition for the Identity task.

In the A_U+ condition, the actor has a false belief that the red object is in the box. In the Location task, both 2-Systems and early mindreading accounts would predict no response facilitation; anticipatory motor cortex activation would not occur as the participant tracks the actor's registration (Fig. 2e) or belief (Fig. 2f) that an undesired object is present. As indicated above, the accounts diverge when forecasting outcomes in the Identity task. A 2-Systems viewpoint, predicts fastest responding in the A_U+ condition (Fig. 2g); this is a *seemingly* inappropriate result given the actor's goal-directed action towards a blue object. The rationale behind our prediction is that motor cortex activation is triggered when System 1 erroneously tracks that the agent last registered

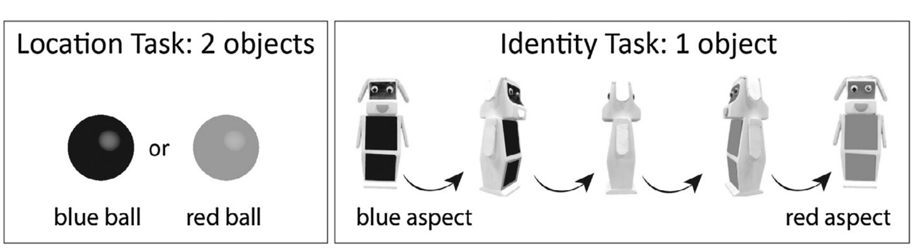

Fig. 1. Objects featured in the Location and Identity tasks.

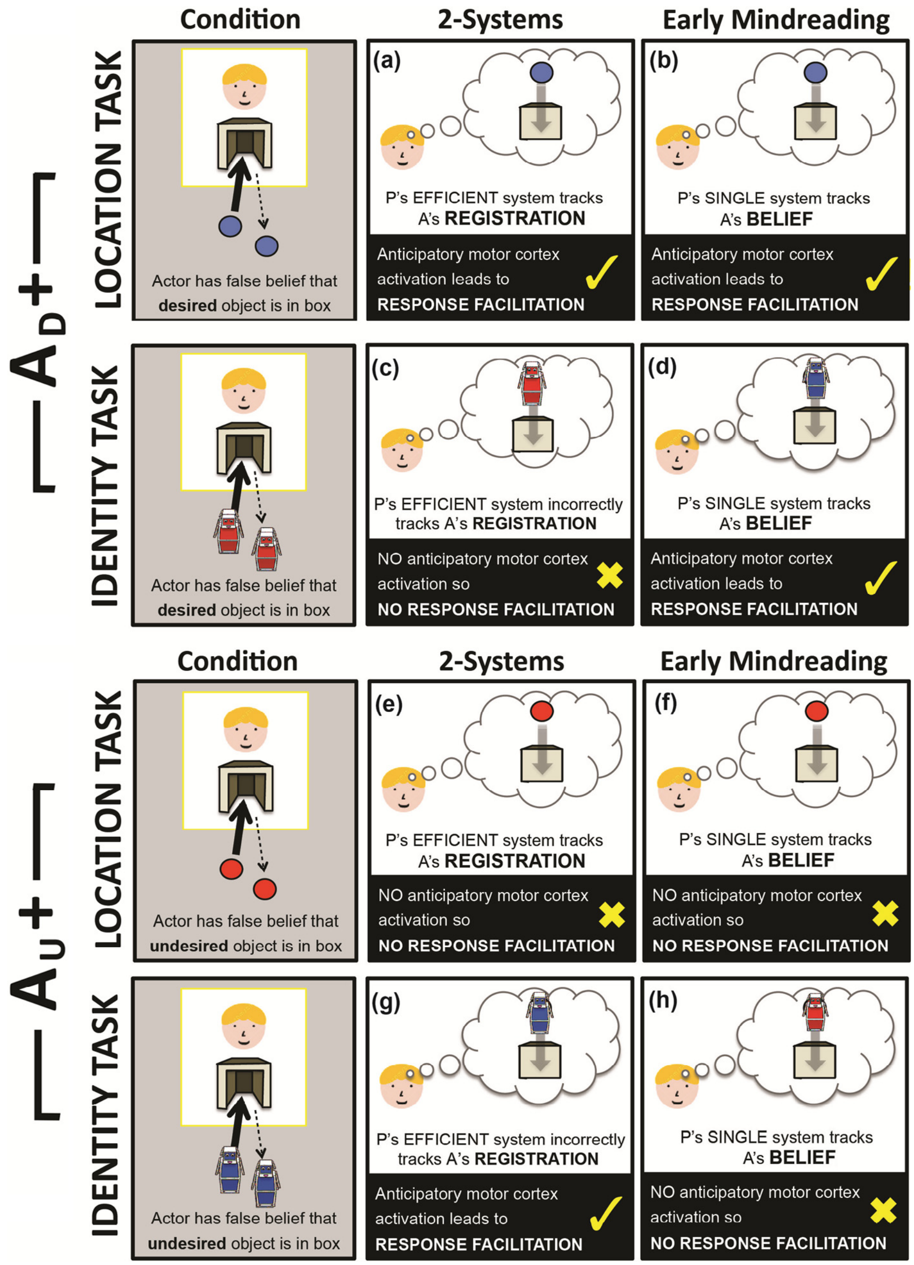

Fig. 2. A schematic representation of processes underlying the Location and Identity hypotheses; the predictions from a 2-Systems account are compared with an early mindreading standpoint. The solid black arrows in the 'Condition' panels indicate the path of the object witnessed by the actor. The dashed arrows show the path of the object when the actor's view was occluded. In this example, the agent desires blue objects and ignores red objects. Note: P = Participant; A = Actor.

a blue object in the box. This contradicts the early mindreading prediction that there would be no response facilitation in this condition (Fig. 2h), and that speediest responding will occur in the A_D+ condition for both tasks.

To summarize, the current investigation marries methodological ideas from a looking time study (Low & Watts, 2013) with an electroencephalogram study (Southgate & Vernetti, 2014) to yield a new behavioural task that allows us to accurately measure the extent to which representing beliefs about an object's identity is a signature limit of the efficient mindreading system. Our dependent variables are error rates and reaction times. Error rates reveal participants' accuracy levels, thereby serving as an explicit measure of belief reasoning. Our reaction time measure reflects the extent to which mental state processing is affected by System 1's implicit tracking of belief-like states. In sum, we use anticipatory motor activation as a proxy for action anticipation, which in turn is indexed by facilitated response time. Dissociations in reaction time patterns within location and identity tasks would converge with previous evidence that suggest adult humans have not one but two systems for tracking and ascribing beliefs.

2. Experiment 1

2.1. Method

2.1.1. Participants

Participants were 40 right-handed adults (19 females and 21 males) who were recruited from the Victoria University of Wellington campus and local businesses in exchange for a coffee voucher.

Participants had an average age of 32.7 years (Range 18–63). All participants signed informed consent forms before participating and were debriefed orally at the end of the session. The University Human Ethics Committee granted ethical approval prior to commencement.

2.1.2. Design

To test our hypotheses we employed a 2 (Task: Location, Identity) × 4 (False-Belief Condition: A_D+, A_U+, A_D−, A_U−) within-subjects experimental design. Our design concentrated on false belief reasoning and did not include true belief conditions. First, we directly followed Southgate and Vernetti's (2014) method that cleverly allowed for the generation of opposing action predictions using only two different false-belief scenarios (see also Krupenye, Kano, Hirata, Call, & Tomasello, 2016; Southgate, Senju, & Csibra, 2007). Second, our primary prediction was that the relative ease of A_D+ and A_U+ would reverse across different false-belief scenarios. As in Low and Watts (2013), even without true belief data, it is possible to illuminate the cognitive processes underlying different mindreading abilities by zeroing in on dissociations between object-location and object-identity performances.

Participants experienced four familiarization trials. Half of them saw trials in which an actor had a preference for blue objects and the other half were familiarized with an actor's preference for red objects. They then progressed to the test trials in which they experienced one block of the Location task trials and one block of Identity task trials (order counterbalanced). We also manipulated the instructions so that half of the participants were directed to focus on an actor's behaviour and the other half were instructed to focus on her mental state. These instructions were presented prior to the familiarization videos, and once again before the test phase commenced. Given that this did not affect participants' behaviour we collapsed the data in these conditions.

2.1.3. Stimuli: familiarization

Each participant watched four familiarization videos. Two of the videos featured a blue object and two featured a red object. In the Blue Colour Preference condition each video began with an actor seated at a table. On the table directly in front of the actor was a lidded box, with an opening that faced the participant. An object (a toy car or toy duck) appeared in the foreground and moved towards the box. When the object was blue (Videos 1 and 3) the actor smiled and exclaimed, "Yay!" (Fig. 3a). The object eventually entered the box and was no longer visible to the actor. The actor then lifted her right hand from the table and opened the box's lid to retrieve the object. The final frame showed a smiling actor holding the desired object aloft (Fig. 3b). If the object was red (Videos 2 and 4), the actor frowned and uttered, "Yuck!" as it appeared and moved towards the box (Fig. 3c). The actor did not retrieve it when it entered the box, instead remaining motionless until the final frame (Fig. 3d). The four videos in the Red Colour Preference condition showed the same events except that the actions of the actor were reversed; she retrieved the red objects and never the blue. The video dimensions were 19.5 cm × 16.5 cm and the total duration for four videos (including 1000 ms fixation crosses separating each one) was 1 min 40 s (see examples in Supplementary Materials). The aim of this phase was to familiarize participants with the actor's colour preference and goal: she desires blue (or red) objects and will act to obtain them, and she does not desire red (or blue) objects and thus will not act. Following the familiarization phase the participants either proceeded to the Location task or to the Identity task (order counterbalanced).

2.1.4. Stimuli: test phase

Each test trial consisted of a sequence of ten video stills featuring the same actor and setting of the familiarization trials. The stills (19.5 cm × 16.5 cm) were presented in chronological order and showed the induction of a false belief in an actor, achieved by changing the location of an object when the actor's view was occluded. The challenge for the participant was to quickly and accurately select the most appropriate outcome of the sequence (from a choice of two) based on the familiarization phase. A complete test trial comprised a fixation frame (1000 ms), followed by ten video stills (each 700 ms). The tenth still had a yellow border, to facilitate anticipation of the outcome phase. At the end of each trial the participant was presented with a choice of two images, side by side (each 8.4 cm × 6.4 cm), in which the actor was either reaching or not reaching for the box (see Fig. 4).

2.1.5. Stimuli: conditions

The participants experienced four conditions in each task. For ease of understanding we describe the conditions in detail below. In each case, the actor desires blue, not red, objects. In two of the conditions the actor falsely believes a blue object is present (A_D+)

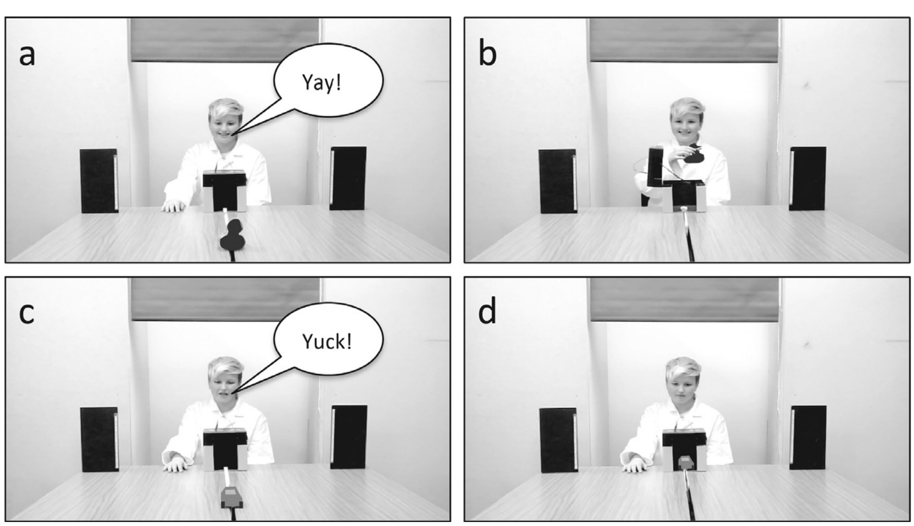

Fig. 3. 'Blue Preference' familiarization videos: An actor exclaims, "Yay!" as a blue object appears and moves towards a box (a). When the object enters the box she opens the lid and retrieves it (b). When a red object appears the actor says, "Yuck!" (c), and remains motionless when it enters the box (d). The actor's behaviour is reversed in the 'Preference Red' familiarization videos.

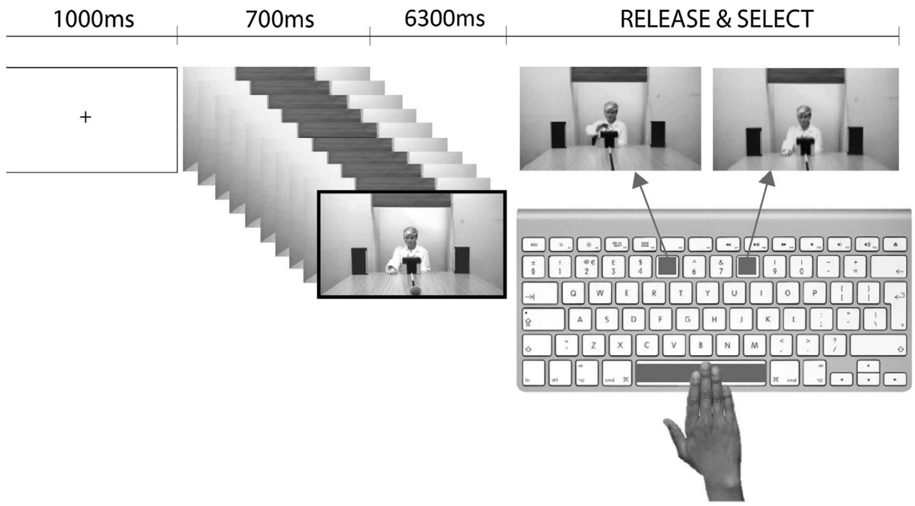

Fig. 4. A schematic diagram showing the timeline of a typical test trial in the Location and Identity tasks.

or absent (A_D-). In the other two conditions the actor falsely believes that a red object is present (A_U+) or absent (A_U-). The critical manipulation between tasks is the type of object used. In the Location task the object is either a blue or a red ball, whereas in the Identity task there is a single object that is blue on one side and red on the other (see Fig. 1). The dual aspect nature of this object is revealed to the participants in a 20-s video clip in which the object appears on the table and turns 180 degrees anticlockwise four times while the actor sits behind a blind.

A_D+ condition: Fig. 5 shows how the actor (A) is induced to falsely believe that a preferred blue object is in the box ($_D+$). In frames 1–4 she sees that the object emerges in the foreground and then enters the box. In frame 5 a blind is lowered, so that in frames 6–8 the actor does not see the object leave the box. Following the final frame, signaled by a yellow border, the participant must choose the most likely event from a choice of two pictures. In the Location task (Fig. 5a) the participant and the actor both see the movements of a blue ball, whereas in the Identity task (Fig. 5b) the actor sees a blue dog whilst the participant sees a red dog. We expected low error rates in outcome selections for both tasks; participants should ascribe that the actor falsely believes a desirable object to be in the empty box. In the Location task, we predicted that participants would react quickest in this condition because responding would be implicitly and efficiently facilitated by System 1's fast paced tracking of registrations, instigating motor cortex activity which occurs in anticipation of another's action. In the Identity task we postulated that response times would not be facilitated; System 1 would mistakenly track the relation between the actor and the red, *undesired*, object, which would *not* trigger anticipatory activity in the motor cortex.

A_U+ condition: In the A_U+ condition, the actor watches a red object enter the box and but does not see it leave when her view is masked by a blind (Fig. 5c and d). In both the Location and Identity tasks we expected that participants would accurately select the outcome in which the actor does *not* reach for the box; the actor falsely believes that the object is present but does not wish to retrieve an undesired toy. We also predicted that there would be no efficient response facilitation in the Location task. However, in the Identity task we postulated that participants' responses would be implicitly and efficiently facilitated, leading to fastest reaction times in the A_U+ condition. Our rationale was that System 1 would incorrectly track the actor's registration of a blue, not red, object; it would fail to take into account how the actor perceives the dual aspect dog and would trigger motor cortex activity in anticipation of a reach response. System 2 ultimately overrides the efficient response facilitation by reasoning that the actor believes there are two different dog-robots across the multiple trials (one blue and one red), just as there are two different blue and red objects in the familiarization trials. She believes that the red one is in the box so will not reach for the box. The crucial reaction time prediction rests on the existence, or not, of a signature limit in the ability to predict action in others based on the subjective nature of their beliefs.

A_D- condition and A_U- conditions: In these conditions the actor is led to believe that either a desired or undesired object is absent (see Fig. 6). Frames 1–4 show how the object emerges from the box and leaves the scene. The blind is then lowered and the object returns to the box, invoking a false belief in the actor (frames 5–8). We expected that participants would explicitly and flexibly select the accurate 'no reach' outcome whether or not the object was preferred, based on the actor's false belief. There would be no reason to expect motor cortex activity during the anticipatory phase in these conditions; System 1 would implicitly and efficiently track the actor's registration that the object is not in the box.

2.1.6. Procedure

Participants, wearing headphones, sat at a Dell Latitude E5440 laptop (31 cm × 17.5 cm screen). All stimuli presentation and instructions to the participant were entirely developed and run using E-Prime 2.0. Participants were guided through the task phase via on-screen directions. General instructions, available to all participants, explained the format of the test trials and provided the correct procedure for responding. These procedural instructions were identical for both tasks: "You will see a series of images, one after the other. These are 'stills' taken from videos, like the ones you just watched. The last image in the series will have a yellow border, like this...then you will see two images. Your task is to select the image that best concludes the series as QUICKLY and ACCURATELY as possible." Each trial started with an instruction to press and hold the spacebar with the right hand. It was stressed that the spacebar should not be released until the two images appeared. When ready, the participant was told to click on the "5" key for the left-side image or the "8" key for the right-side image. Participants then proceeded to the trials in both tasks; the only difference was that the Identity task first presented a short clip of a rotating object before continuing (see Fig. 1). For each task,

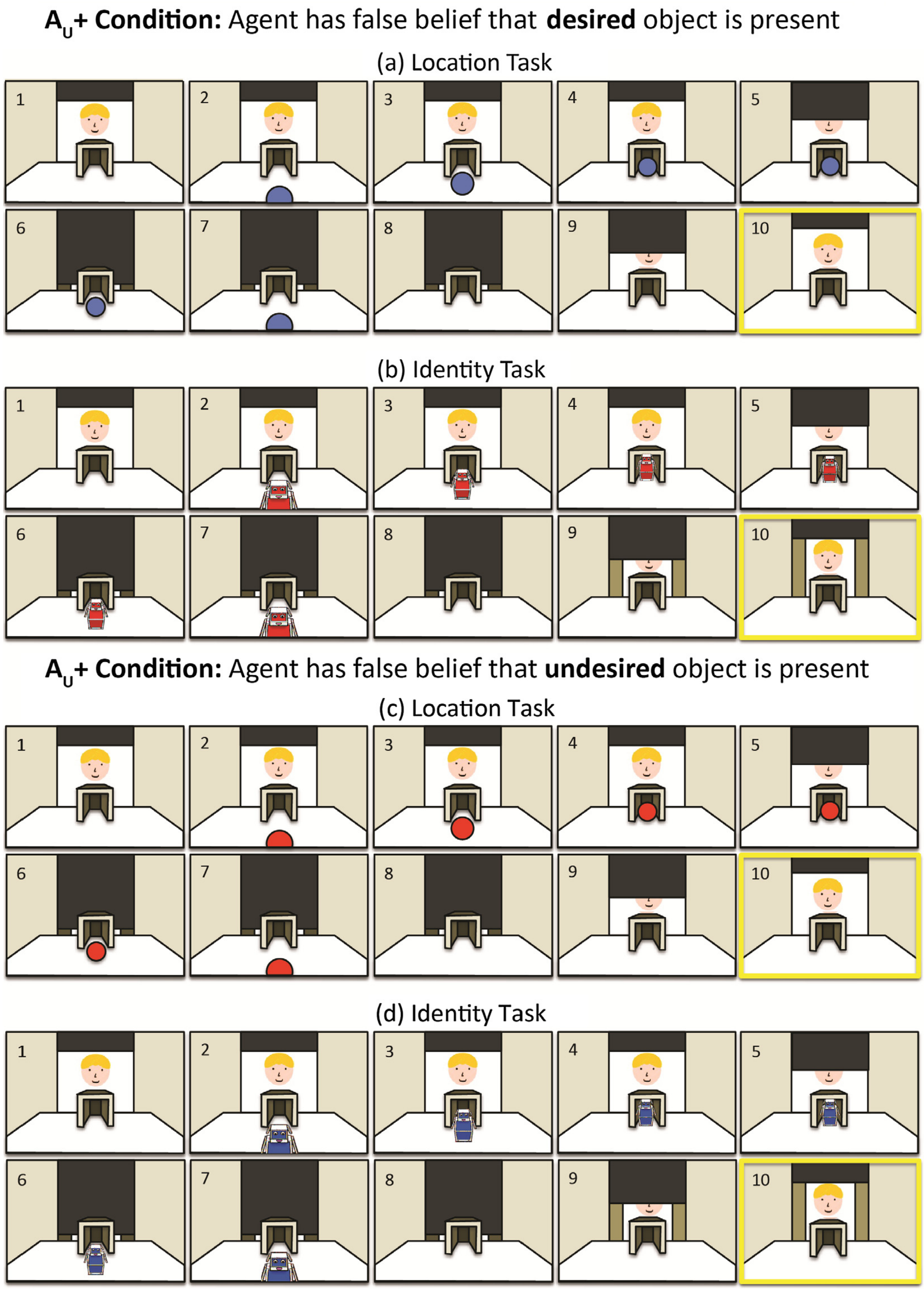

Fig. 5. A schematic depiction of the sequence of stills for the A_D+ and A_U+ conditions in the Location and Identity tasks. In the Location task, both participant and actor see a blue ball, whereas in the Identity task the dual-aspect object requires that the participant sees a red-object while the actor sees a blue object.

40 sequences were presented in a pseudorandom order; comprising five cycles of four different conditions (see Fig. 4), each with a counterbalanced left or right outcome image. Thus, participants experienced 80 trials in total. No performance feedback was given after individual test trials to minimize trial time and distraction. On completion of the two tasks participants were debriefed and their data collected.

To address the potential variability of untrained performances (Sternberg, 2004), a training phase exposed participants to 8 practice trials with feedback. These were undertaken before each block of experimental trials and comprised each of the four trial types paired with counterbalanced outcomes (reach outcome on right versus left side). To ensure that training was effective we set an accuracy threshold of 80%. This required that participants had to select the correct answer in 7 out of 8 trials before they could move on to the experimental phase. If this threshold was not met the participants were required to repeat the training block.

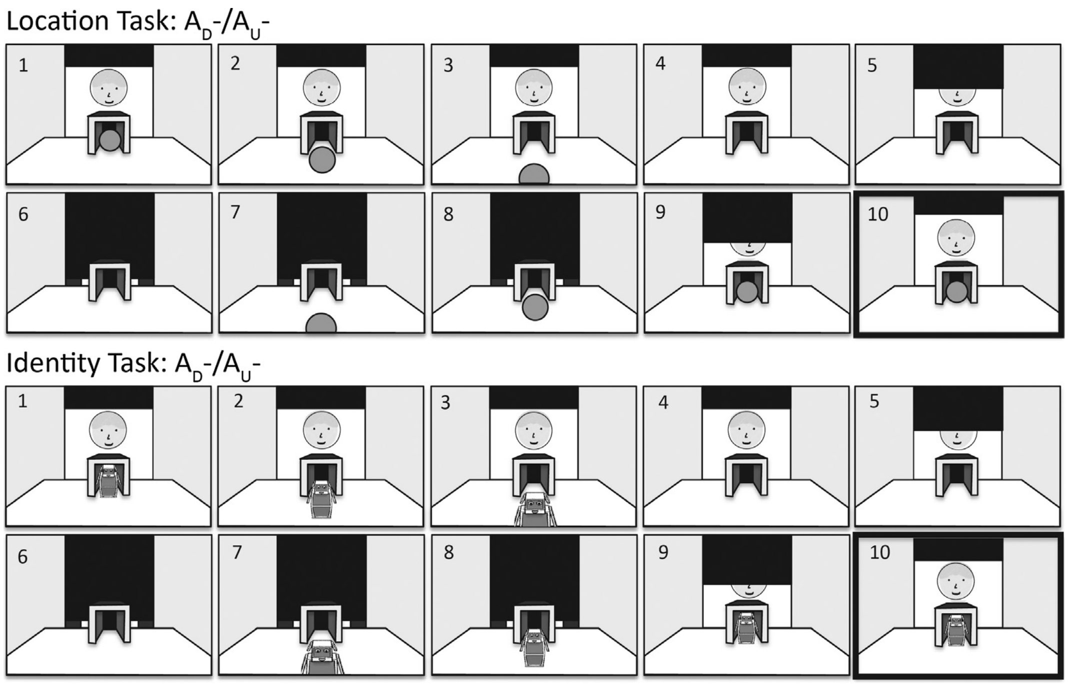

Fig. 6. Sequence of stills for the A_D- and A_U- conditions in the Location and Identity tasks.

2.2. Results

Statistical analysis was only undertaken on correct responses, in which the participant selected a response that was consistent with the actor's false belief. Error rates are reported separately in Section 2.2.2. Outliers were excluded from the analysis of response times on the basis of being 3 standard deviations away from the mean response time (between 1% and 2% of individual responses across the four conditions of the Location task and between 1.5% and 2.5% across the four conditions of the Identity task). Initial analysis revealed no colour preference or task order effects. Furthermore, there was no difference in mean response times between the first and second half of trials in each condition. Tests for normality revealed a positive skew in reaction times and error rates. We performed a logarithmic transformation of this data before proceeding with further statistical analysis. Transformed and untransformed means for response times are presented in Appendix A (Tables A.1 and A.2) and for error proportions in Appendix B (Tables B.1 and B.2). Greenhouse Geisser corrections were used whenever the assumption of sphericity was violated (that is, when the Mauchly's test statistic was significant).

2.2.1. Response times

The 2-Systems and early mindreading theories both predict that reaction times will be fastest when participants expect the agent to reach for the desired blue object based on her false belief (see Fig. 2). Our Location Hypothesis was confirmed when we found that reaction times were at least 348 ms faster in the A_D+ condition than the other conditions. The Identity task allowed us to disentangle the theories by revealing that participants responded at least 312 ms faster in the A_U+ condition than in all other conditions, as predicted in our Identity hypothesis. Notably, an early mindreading approach would instead predict faster responding in the A_D+ condition.

Our critical predictions were tested in a 2 (Task: Location, Identity) × 2 (False-Belief Condition: A_D+, A_U+) ANOVA. In these trials the agent falsely believed that an object was in the box. A significant Task ∗ False-Belief Condition interaction, $F(1,39) = 26.53$, $p < 0.001$, $\eta p^2 = 0.41$, confirmed a selective response time facilitation effect (see Fig. 7a). Participants were faster to respond when they expected the agent to reach for the desired (blue) single-aspect object in the Location task, but in the Identity condition they were faster to respond when the agent falsely believed that the *undesired* (red) object was in the box.

All conditions were investigated in a 2 × 4 repeated measures ANOVA with Task (Location, Identity) and False-Belief Condition (A_D+, A_U+, A_D-, A_U-) as within-subjects factors. There was no main effect of Task, but there was a main effect of False-Belief Condition, $F(2.19,85.23) = 32.73$, $p < 0.001$, $\eta p^2 = 0.46$, and an interaction between Task and False-Belief Condition, $F(1.86,72.69) = 19.66$, $p < 0.001$, $\eta p^2 = 0.34$. To investigate the interaction further we separated the data by Task.

Location task: As predicted in the Location Hypothesis, participants performed fastest in the scenario where the actor falsely believed the desired object was in the box (see Fig. 7b). A repeated measures ANOVA revealed a main effect of False-Belief Condition, $F(1.49,57.97) = 32.18$, $p < 0.001$, $\eta p^2 = 0.45$. Following Bonferroni-corrected pairwise comparisons it was determined that the mean response time for the A_D+ condition was faster than that of the A_U+ condition, $t(39) = 5.04$, $p < 0.001$, the A_D- condition, $t(39) = 7.19$, $p < 0.001$, and the A_U- condition, $t(39) = 5.20$, $p < 0.001$. Response times were significantly longer in the A_D- condition than in the A_U+, $t(39) = 4.25$, $p = 0.001$, and A_U-, $t(39) = 5.80$, $p < 0.001$, conditions. There was no difference in mean reaction times between the A_U+ and A_U- conditions.

Identity task: The Identity Hypothesis was supported, in that participants were fastest to respond in the condition in which the actor had a false belief that an undesired object was in the box. Again, there was a main effect of False-Belief Condition, $F(1.97,76.99) = 18.71$, $p < 0.001$, $\eta p^2 = 0.32$. Bonferroni-adjusted pairwise comparisons showed that response times in the A_U+ condition were significantly faster than in the A_D+ condition, $t(39) = 3.96$, $p = 0.002$, the A_D- condition, $t(39) = 5.40$, $p < 0.001$ and the A_U- condition, $t(39) = 5.07$, $p < 0.001$. There were no other differences (see Fig. 7b).

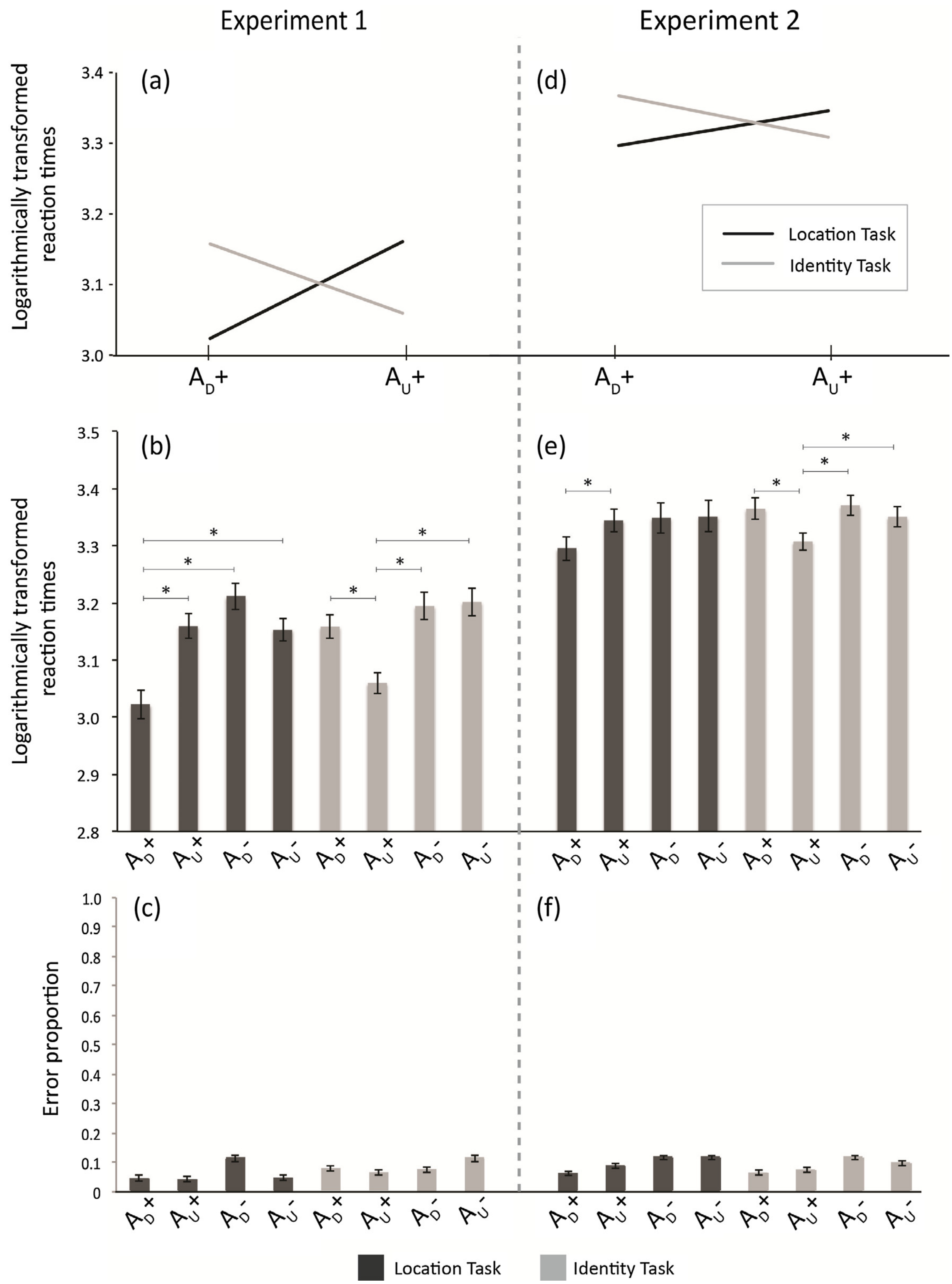

Fig. 7. The Task * False-Belief Condition interactions (a & d) support the Location and Identity Hypotheses for Experiments 1 and 2. Bar charts show the logarithmically transformed response times (b & e) and mean error proportions (c & f) for the Location and Identity tasks. Error bars represent the standard error of the mean. Note: * significance level, $p < 0.01$.

2.2.2. Errors

Error rates served as a measurement of explicit belief reasoning; overall, participants displayed high performance levels during the training and test trials as revealed by low mean error proportions. We found no evidence of speed-accuracy tradeoffs in the critical A_D+/A_U+ conditions; lower response times for the A_D+ condition in the Location task were not accompanied by significantly greater errors in this condition. Similarly, such a reverse pattern was not found in the Identity task; there was faster responding in the A_U+ condition, but no difference in mean error proportions across conditions. For the practice trials, 95% of the participants, who first experienced the Location task, and 93% of those starting with the Identity task, required just one practice block (of 8 trials) before proceeding to the test trials. The remaining two participants in the Location task, and three in the Identity task, required two practice blocks before moving on to the experimental trials. All participants were ready to proceed to trials after a single block of practice trials in their second task. In the test trials, the overall error rates were low (6% and 9% in the Location and Identity tasks respectively; see Fig. 7c for mean proportion of errors in each condition). Tests for normality revealed that the error data was positively skewed. To account for this, all analyses of variance were performed on logarithmically transformed data.

In keeping with the reaction time analysis, the initial examination was hypothesis-driven: a 2×2 ANOVA between Task (Location, Identity) and False-Belief Condition (A_D+, A_U+). Contrasting with reaction time analysis there was no Task $*$ False-Belief Condition interaction, and no main effect of condition. However, a main effect of Task, $F(1,39) = 10.38$, $p = 0.003$, $\eta p^2 = 0.21$, revealed that the proportion of errors was lower in the Location (logarithmically transformed $M = 0.02$) than the Identity ($M = 0.03$) task. This main effect was also found in our subsequent 2×4 repeated measures ANOVA with Task (Location, Identity) and Condition (A_D+, A_U+, A_D−, A_U−), $F(1,39) = 10.38$, $p < 0.001$, $\eta p^2 = 0.3$, with Identity errors ($M = 0.034$) being greater than Location errors ($M = 0.025$). There was also a main effect of False-Belief Condition, $F(2.60, 101.22) = 2.92$, $p = 0.003$, $\eta p^2 = 2.92$ and an interaction between Task and False-Belief Condition, $F(2.50, 97.67) = 4.09$, $p = 0.013$, $\eta p^2 = 0.01$. To examine this further, we considered each task separately.

Location task: A repeated measures ANOVA determined that mean error proportions differed between the four conditions, $F(2.36, 92.06) = 4.92$, $p = 0.006$, $\eta p^2 = 0.11$. Pairwise comparisons with Bonferroni corrections revealed that participants made more errors in the A_D− condition than in the A_D+ condition, $t(39) = 3.00$, $p = 0.045$, or A_U+ condition (see Appendix B2 for descriptive statistics). We note that participants were significantly slower and more error-prone in the A_D− condition. Whilst not the focus of our predictions this phenomenon may indicate an approach bias, where the presence of the blue ball in the box in the final frame influences the participant's 'reach/no reach' decision.

Identity task: An analysis of variance revealed no significant difference in mean error proportions across conditions, $F(2.75, 107.24) = 2.03$, $p = 0.119$ (see Appendix B2).

2.3. Discussion

Response times were compared across four conditions in two separate tasks. Central to our predictions, the Task $*$ False-Belief Condition interaction for response times revealed that performance was dependent on task. Supporting the Location Hypothesis, participants in the Location task were faster to respond when the actor had a false belief that the desired object was in the box (A_D+ condition). This result concurs with the findings of Southgate and Vernetti (2014). Utilizing their paradigm the current study went a step further by revealing that adults behave differently when tracking beliefs involving identity. As predicted in the Identity Hypothesis, they were faster to respond in the A_U+ condition, where the actor falsely believed that an undesired object was in the box. One explanation for this behavioural distinction derives from the 2-systems account: the efficient mind-reading system is able to track an actor's registration of an object's *location* but it cannot process how an object's *identity* is represented by the actor.

Consider participant performance in the Location task: in the A_D+ condition, the participant and actor see a desired blue ball enter the box. Then the participant, but not the actor, witnesses the ball leaving the box. System 2 ascribes that the actor will retrieve the ball because she likes blue things and she *thinks* it is in the box. The crux of our findings however, is revealed in our implicit measure. According to the 2-Systems theory, as these events unfold the participant's System 1 tracks the actor's registrations of the changing environment. At the onset of the anticipatory (yellow border) period, System 1 records that the actor registered the preferred object in the box. We propose that the faster responses for the A_D+ condition in the Location are the result of implicit and efficient System 1 processes (tracking of registrations, not belief states) that lead to activation of the motor cortex in anticipation of a reach response from the actor.

Support for the 2-Systems approach is provided by the response time findings in the Identity task. Consider a participant's experience in the same A_D+ condition. Here, the dual identity dog-robot enters the box and then leaves while the actor's view is masked (Fig. 5b). System 2's processing allows flexible reasoning (e.g. "I saw a red dog enter the box and then leave, but she thinks a blue one is there, so she'll reach for the box"), but we do not find the same pattern of faster reactions in A_D+ condition because of a signature limit operating upon System 1. This inflexible system is not set up to process how others perceive an object and thus tracks the *location* of the dog-robot but not *how it appears* to the agent. In this condition the motor cortex is not activated in anticipation of a reach to the box because System 1 tracks, efficiently but incorrectly, that the actor registered a red dog-robot in the box and thus will remain motionless.

Response times from the A_U+ condition provide further evidence of 2-Systems processing. In the Location task, the participant and actor see the undesired red ball enter the box, but only the participant sees the ball leaving the box. System 1 tracks the actor's registrations and System 2 ascribes the actor's beliefs regarding the location of the unwanted object. Unsurprisingly, participants respond correctly that the actor will remain motionless, and they do so significantly more slowly in this condition than the A_D+ condition, indicating that there was no response facilitation due to anticipatory motor cortex activation.

It is the performance of participants in the A_U+ condition of the Identity task that provides key evidence that adult humans possess more than one TOM system. In this condition, the dual aspect dog-robot enters the box (red side facing the actor), and then exits while her view is occluded (Fig. 5d). Participants correctly judged that the actor would not reach for the box and, remarkably, they were faster to do so. Significantly faster response times in this condition compared to the other conditions cannot be explained by an early mindreading approach (or by applying behaviour rules). The explanation given here is that while System 2 can explicitly reason that the actor will not reach into the box because she believes it to contain a red object, System 1 fails to account for the way in which the actor identifies the dog (as a red, not blue object) and continues to track the relationship between actor, location and *blue* object. As a result, the A_U+ response times in the Identity condition are facilitated by motor activation, as they are in the A_D+ condition of the Location task. It is noteworthy that there is no statistical difference in response times between the A_D+ (Location) and A_U+ (Identity) conditions, both of which, we argue, are accelerated due to efficient System 1 processing and the follow-on effects of anticipatory motor cortex activity. Crucially, our main findings were replicated in a second experiment in which we slightly modified the task instructions.

3. Experiment 2

In Experiment 1, we found no behavioural effect when participants were asked to either focus on the actor's mental state or on her behaviour. As both these instructions required the participant to attend to the actor in some way, Experiment 2 sought to determine if an instruction that directed attention away from the agent would influence the overall pattern of participants' performances as compared to Experiment 1.

3.1. Method

3.1.1. Participants

Participants were 20 students from Victoria University of Wellington who participated in partial fulfillment of a course requirement. The sample included 16 females and had an average age of 18.5 years (Range 18–20). Consent and ethical approval was granted as in Experiment 1.

3.1.2. Design and procedure

The design and procedure were identical to that of Experiment 1, except for a minor change to the task instructions; rather than being asked to focus on the actor's mental state or behaviour prior to the familiarization videos and test phase, participants were instructed to focus on the object's location. Seventeen participants proceeded to the test phase after one block of practice trials, the remaining three required two blocks.

3.2. Results

Participants' explicit belief-reasoning was highly accurate as shown by the error data. Implicit mindreading differed according to task, revealed by the False-Belief Condition * Task interaction in response times. The crucial finding was that for False-Belief Conditions A_D+ and A_U+, reaction times were reversed; in the Location task participants were significantly fastest to respond when the actor falsely believed that a desired-colour object was in the box whereas in the Identity task they responded most rapidly when the actor falsely believed that an undesired-colour object was in the box. Faster response times in these conditions were not the result of speed-accuracy tradeoffs.

As in Experiment 1, incorrect responses and outliers were excluded from the analysis of response times. Outliers represented between 1% and 3.5% of individual responses across the four conditions of the Location task and between 0.5% and 2.5% across the four conditions of the Identity task. Error rates are analyzed separately below. Response times and error proportions were positively skewed so analyses of variance were performed on logarithmically transformed data. ANOVA's revealed that neither preference or task order affected performance, and mean response times did not differ between the first and second half of trials in each condition.

3.2.1. Response times

Performance was dependent on task, even under slightly different conditions (a modification of the instructions given to participants). A hypothesis-driven 2 × (Task: Location, Identity) × 2 (False-Belief Condition: A_D+, A_U+) repeated measures ANOVA was undertaken in order to examine the conditions in which the agent had a false belief that the object was *present*. Crucially, we revealed an interaction, $F(1,19) = 22.51$, $p < 0.001$, $\eta p^2 = 0.54$; participants were quicker to respond when they expected the agent to reach for a desired object in the Location task, but were quicker in the Identity task when the agent was not explicitly expected to reach for undesired object (see Fig. 7d). Whilst explicitly accurate, participants' implicit mindreading was adversely affected by limits to the efficient system; in the Identity task it failed to account for the way in which the agent perceived the object.

A 2 (Task: Location, Identity) × 4 (False-Belief Condition: A_D+, A_U+, A_D−, A_U−) repeated measures ANOVA determined that there was an interaction between Task and False-Belief Condition, $F(3,57) = 8.68$, $p < 0.001$, $\eta p^2 = 0.31$. We also found a main effect of False-Belief Condition, $F(3,57) = 4.58$, $p = 0.006$, $\eta p^2 = 0.19$. Subsequent analysis considered mean response times for each task in turn (see Fig. 7e).

Location task: A repeated measure ANOVA determined a main effect of False-Belief Condition, $F(2.19,41.53) = 4.18$, $p = 0.02$, $\eta p^2 = 0.18$. Pairwise comparisons with Bonferroni corrections revealed that response times in the A_D+ condition were significantly faster than those in the A_U+ condition, $t(19) = 2.94$, $p = 0.046$. There were no other significant differences, though the pattern of response times does trend towards the findings of Experiment 1.

Identity task: Analysis showed that mean response times differed between conditions, $F(3,57) = 13.93$, $p < 0.001$, $\eta p^2 = 0.42$, with participants responding significantly faster in the A_U+ condition than in the A_D+ condition, $t(19) = 5.70$, $p < 0.001$, the A_D− condition, $t(19) = 6.30$, $p < 0.001$, or in the A_U− condition, $t(19) = 4.30$, $p < 0.005$. All other comparisons were non-significant. This replicates the findings in Experiment 1, in that participants' responses were significantly faster when the actor falsely believed the unwanted dog-robot was present.

3.2.2. Errors

Overall, explicit responses in Experiment 2 revealed low error rates for the Location and Identity tasks (10% and 9% respectively; see mean error proportions in Fig. 7f). There were no signs of a speed-accuracy tradeoff in the critical (A_D+/A_U+) conditions; faster response times in one condition over the other was not accompanied by significantly higher errors in that condition. A 2 (Task: Location, Identity) × 2 (False-Belief Condition: A_D+, A_U+) ANOVA revealed no difference in error rates, between tasks or conditions, when the agent falsely believed that an object was in the box, $F(1,19) = 0.21$, $p = 0.65$. Following on from this we ran a 2 (Task: Location, Identity) × 4 (False-Belief Condition: A_D+, A_U+, A_D−, A_U−) repeated measures ANOVA which also revealed no interaction, $F(2.84,53.91) = 0.18$, $p = 0.90$. Further analysis revealed no significant difference in error proportions across the Location task conditions, $F(2.82,53.65) = 1.59$, $p = 0.20$ or Identity task conditions, $F(2.19,41.53) = 0.87$, $p = 0.44$. Unlike in Experiment 1, we found no evidence of a possible approach bias in the Location task's A_D− condition.

3.3. Discussion

There was no notable effect of the instruction manipulation on the pattern of performances. However, the findings did reveal that reaction time was appropriately fast in a location scenario that involved tracking an agent's false belief that a desired object was present. By contrast, reaction time was unduly fast in an identity scenario that involved tracking an agent's false belief that an undesired object was present. Crucially, Experiment 1's dissociation of behaviour between two different tasks was preserved in Experiment 2.

4. General discussion

Performing a false-belief task with a dual-aspect component revealed a blind spot in the efficient mindreading system. In Experiments 1 and 2 we tested the extent to which participants' action predictions were affected by the specific content of an agent's false beliefs. In each trial, participants were instructed to select the appropriate outcome of a sequence of events featuring an actor with a clear goal. In one condition (A_D+), the actor watched a desired object enter a box in front of her, but did not see it subsequently leave. Participants responded accurately if they predicted that the actor would reach to retrieve it. In the remaining three conditions, 'no reach' was the correct response as the actor falsely believed that the box was empty (A_D-, A_U-), or that it contained an undesired object (A_U+). We assessed performances across two tasks; in the Location task all conditions involved either a blue or red single-aspect object, whereas in the Identity conditions there was only one, dual-aspect (red *and* blue) object. As expected, participants were highly accurate in their responses across all trials, but the focus of our study was the *pattern* of reaction times resulting from the four differing conditions.

We conjectured that, in the Location task, lower-level mindreading processes rapidly triggered motor cortex activity in the A_D+ condition, in anticipation of the actor's reach for a desired blue ball. However, this appropriate response was not mirrored in the Identity task. Here, System 1 failed to predict the actor's action in the A_D+ condition because it was subject to a signature limit over the processing of how the actor perceived the dual object. High-level processing by System 2 allowed participants to effortfully (and correctly) reason, "I see it as red, but she sees it as blue; she likes blue things therefore she will reach for the box", but the response time was not expedited. System 1 unduly triggered motor cortex activation in the A_U+ condition, incorrectly tracking the relation between the actor, object location and *desired* (i.e., blue) object. The blind spot was revealed by the fastest response times in this condition. To predict the actor's probable action, the participant must infer (from the circumstances in which the actor encounters the object) that she will register it as being blue all over. This is no problem for a flexible mindreading system: someone who only sees one side of a blue ball is likely to assume that it is blue all over because this sort of thing tends to have a uniform colour (or at least she would not expect it to be precisely the colour she dislikes on its reverse side). However, because this requires an appreciation of *how* an object is perceived from different viewpoints, we suggest that this type of processing it is not within the scope of an efficient system.

Testing System 1 signature limits often relies on documenting that efficient mindreading supports tracking others' mental ascriptions of where an object is located or what is or is not perceptible to someone, but not how someone identifies an object from a different perspective or viewing angle (Low & Watts, 2013; Low et al., 2014; Mozuraitis et al., 2015; Surtees, Butterfill, & Apperly, 2012; Surtees, Samson, & Apperly, 2016). Carruthers (2015, 2016) suggests that there is a confound because different performances between object-location and object-identity tasks might be instead due to non-mental content; identity tasks often involve spatial rotation to represent another's perspective. We did find that participants made more errors in the Identity task, but overall their accuracy was very high in both tasks. The claim from the early mindreading viewpoint, that tasks involving a dual-aspect object place great demands on executive functioning, do not explain the dissociation of performances across the two tasks discovered in this research. Importantly, signature limits on efficient mindreading have also been documented with identity tasks that do not involve rotation (e.g., Fizke et al., 2013). Furthermore, performance on independent measures of mental rotation ability are not correlated with the appreciation of how an object that is simultaneously visible to the self and other can give rise to different representations of identity (Hamilton, Brindley, & Frith, 2009).

The study bears on the conjecture that System 1 can modulate motor processes. The reaction times in Location conditions show that belief tracking (of some kind) modulates motor processes; comparison between reaction times in Location and Identity conditions implies that it is System 1 which modulates motor processes; and the fact that reaction times diverge from button selections in Identity conditions suggests that the influence of System 1 on motor processes does not involve System 2 or practical deliberation. Thus we have uncovered something important about how mindreading systems with different processing constraints handle different tasks. Instead of considering two responses to a scenario involving false belief (e.g. anticipatory looking and verbal response), our innovative method considers two aspects of a single response to a scenario involving false belief. It also shows that incompatible predictions can be manifest in a single response. In the Identity conditions, response times indicate one prediction about an observed action whereas button selections indicate a different, incompatible prediction.

The findings from our Experiments 1 and 2 converge with a range of visual perspective-taking studies that have documented limits on people's ability to track how others may experience the same object or scenery in a different way (e.g., Keysar et al., 2003; Masangkay et al., 1974; Moll, Meltzoff, Merzsch, & Tomasello, 2012; Surtees et al., 2012). Further research is needed to examine the extent to which these converging findings reflect the visual saliency of self-perspective in certain mindreading tasks. That said, consider Keysar et al.'s referential communication task where adults had to move objects about a vertical grid according to the directions of a confederate. Participants were aware that only some of the objects were mutually visible, but when asked to "move the small candle" they often mistakenly attended to the smallest candle from their privileged perspective, rather than to the smallest candle experienced from the confederate's perspective. Keysar et al. went to great lengths to reduce the saliency of self-perspective by inviting the participant to set up the array of objects on the grid from the confederate's point of view, making it clear which objects could be seen and which could not. Despite these steps, participants' errors persisted when interpreting the confederate's referential communication, which suggests that the early moments of mental state processing may be relatively less affected by manipulations of low-level visual factors.

Critical to our study was an experimental design that allowed for the teasing apart of opposing mindreading accounts. Within the constraints of the current rationale, advocates of the early mindreading account would predict anticipatory motor cortex activity when the actor falsely believed a desired object was in the box, irrespective of the object's dual aspect; therefore, fastest reactions would occur in the A_D+ condition for *both* tasks. The present findings, then, question how a single-system framework can account for the inappropriately expedited performance in the identity task. Why do adults respond fastest in a scenario where they explicitly expect no response from the agent? Our data also qualifies a rich interpretation of Southgate and Vernetti's (2014) work. While their findings can be claimed as evidence that infants use mental state representations to predict agents' actions, such claims would require that infants were able to generate on-line representations of a person's perspective irrespective of the object's form. We conjecture that inclusion of a dual aspect component into their paradigm, as demonstrated here, would result in inappropriate action-predictions (as shown by anticipatory motor activation) by infants. Early mindreading advocates would put this failure down to task difficulty but the result of this study support the claim that whilst infants accurately predict the actor's action in the Location task, they do so by tracking her registrations. A next step would be to modify the current paradigm to measure anticipatory motor cortex activation via electroencephalography in adults, children and infants. Duplication of the present pattern of findings would augment a growing number of studies that questions the early mindreading stance.

We found that participants were able to track, within limits, whether someone with a false belief would or would not reach for a box to retrieve a desired (e.g., blue) or undesired (e.g., red) object. Supporting Butterfill and Apperly (2016), our findings suggest that it is possible for the efficient tracking of belief and the efficient tracking of desire to jointly inform expectations of others' future actions. System 1 mindreading may be set to track others' *preferences* as a proxy of desire, where a preference describes a relationship between an agent, two outcomes (A and B) and a probability. If so, when our participants repeatedly witness an agent's action resulting in A (reaches for blue things), and never B (reaches for red things), the probability of A increases. Within such a model, representations of preferences allow a minimal mindreader to efficiently expect that when an agent can act either with the goal of reaching for blue things or with the goal of reaching for red things, she will act with the former goal. Further, the part of System 1 that tracks registration as a proxy of belief enables the participant to expect that when the agent acts on the goal involving the blue object, her action will accord with what she registers concerning the blue object. In this way, a minimal model of mind that involves principles linking preferences, registrations and goals can help us to efficiently anticipate others' future actions.

5. Conclusion

In the course of our everyday experiences, we can quickly make impressions about, as well as slowly cogitate over, someone's behaviour. Marrying ideas from a looking time study (Low & Watts, 2013) with an electroencephalogram study (Southgate & Vernetti, 2014), we developed a new reaction time paradigm that successfully differentiated the cognitive systems that underlie those distinct mindreading abilities. We exposed dissociations in the profile of adults' speeded responses over certain phenomena, whereby appropriate response facilitation occurred when tracking false beliefs about location, whilst inappropriate facilitation occurred when tracking false beliefs about identity. Our behavioural data provides new and converging evidence for Apperly and Butterfill's (2009) 2-System's account that adult humans draw upon multiple systems and models of mind for making action predictions.

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Appendix A. Reaction time data for Experiments 1 and 2

See Tables A.1 and A.2.

Table A.1
Logarithmically transformed mean response times.

Task	False-belief condition	Experiment 1 (*n* = 40)		Experiment 2 (*n* = 20)	
		M	*SD*	*M*	*SD*
Location	A_D+	3.02	0.16	3.30	0.09
	A_U+	3.16	0.14	3.34	0.09
	A_D-	3.21	0.14	3.35	0.12
	A_U-	3.15	0.12	3.35	0.12
Identity	A_D+	3.16	0.13	3.37	0.08
	A_U+	3.06	0.12	3.31	0.07
	A_D-	3.19	0.15	3.37	0.08
	A_U-	3.20	0.15	3.35	0.08

Table A.2
Mean response times (in milliseconds).

Task	False-belief condition	Experiment 1 (*n* = 40)		Experiment 2 (*n* = 20)	
		M	*SD*	*M*	*SD*
Location	A_D+	1132.48	474.47	2016.95	480.76
	A_U+	1521.27	480.53	2257.80	470.14
	A_D-	1714.05	553.94	2314.45	640.54
	A_U-	1480.98	421.63	2332.50	664.50
Identity	A_D+	1507.90	496.72	2357.50	483.76
	A_U+	1195.90	416.77	2054.60	332.07
	A_D-	1660.18	601.72	2390.45	465.28
	A_U-	1692.30	650.25	2279.95	450.51

Appendix B. Error data for Experiments 1 and 2

See Tables B.1 and B.2.

Table B.1
Logarithmically transformed mean error proportions.

Task	False-belief condition	Experiment 1 (*n* = 40)		Experiment 2 (*n* = 20)	
		M	*SD*	*M*	*SD*
Location	A_D+	0.02	0.03	0.03	0.03
	A_U+	0.02	0.03	0.04	0.04
	A_D-	0.04	0.05	0.05	0.06
	A_U-	0.02	0.03	0.05	0.04
Identity	A_D+	0.03	0.03	0.03	0.04
	A_U+	0.03	0.03	0.03	0.04
	A_D-	0.03	0.04	0.04	0.06
	A_U-	0.05	0.04	0.04	0.05

Table B.2
Mean error proportions.

Task	False-belief condition	Experiment 1 (*n* = 40)		Experiment 2 (*n* = 20)	
		M	*SD*	*M*	*SD*
Location	A_D+	0.05	0.07	0.06	0.07
	A_U+	0.04	0.07	0.09	0.10
	A_D-	0.12	0.16	0.12	0.16
	A_U-	0.05	0.09	0.12	0.11
Identity	A_D+	0.08	0.09	0.07	0.10
	A_U+	0.07	0.08	0.08	0.11
	A_D-	0.08	0.09	0.12	0.17
	A_U-	0.12	0.11	0.10	0.13

Appendix C. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2016.12.004.

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