Action Prediction:
a Multimodal Techniques Investigation of the Functional Relationship Between Belief-Tracking and Motor Processes

by

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Abstract

Anticipatory responses during action observation can indicate our expectation of an agent's goals. The challenge is that social situations are often more complex, involving instances where we need to perceive and track an agent's false belief to successfully identify and interpret the outcome to which an action is directed. One theoretical possibility is that if motor processes can guide how action goals are understood, it is conceivable—where that kind of goal ascription occurs in false-belief tasks—for motor representations to account for someone's belief-like state. Multiple experiments were conducted to test that possibility. In Experiment 1A, adults (N = 42) were tested in a real-time interactive helping scenario, and the results showed that participants' early mediolateral motor activity (leftwards–rightwards leaning on a balance board) and anticipatory gaze foreshadowed the agent's belief-based action preparation. In Experiment 1B, adults (N = 39) did not show sensitivity to belief in their leaning or eye gaze when participants had to work out the chain of inferences governing the agent's actions. The combined results suggest that small changes in the context can affect adults' ability to spontaneously anticipate and to motorically represent an agent's action. Experiment 2 presented the interactive helping scenario as a multi-trial computerized task. Experiment 2 measured the dynamics of adults' leaning as well as hand trajectories as they attempted

to reach a target object whilst an agent had a true or false belief about the object's location (as a manipulation of motor representations, the agent was also shown as being motorically able or unable to grasp the target object). Replicating Experiment 1A, adults' mediolateral balance during the action anticipation stage took into consideration an agent's false- and true-belief about the target's location. However, there was no evidence that the hand trajectories participants produced to provide a response were influenced by the agent's beliefs. Manipulation of the agent's ability to move did not affect participant's mediolateral balance or the dynamics of their hand trajectories. While in Experiments 1A, 1B and 2, participants were shown the outcome to which the agent's action was directed, in Experiments 3A (N = 51 adults), the task context was changed so that the agent did not present any outcome-directed action and participants were simply instructed to click as fast as possible on the box containing the target object. Experiment 3B (N = 55 adults) was the same as Experiment 3A, except that the task was presented in a go/no-go format. In Experiment 3A, there was no evidence that the agent's belief influenced the degree to which participants' mouse-movement trajectories deviated from a direct path to the object location. In Experiment 3B, the agent's belief had a puzzling effect; participants' mouse movements showed a more conspicuous attraction towards the full box (containing the target object) when the agent had a false-belief as compared to when the agent had a true-belief. While adults' leaning, anticipatory looking and, more tentatively, hand movements, revealed some contribution of fast false-belief tracking, participants across the various experiments did not consistently correct the agent's belief-induced mistake in their final helping action. This thesis will discuss the extent to which motor and mindreading processes may be variously integrated, and that adults may not necessarily use another's belief during overt social interaction or find reflecting on another's belief as being normatively relevant to one's own choice of action.

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Synopsis

When we observe another person performing an action, our motor system becomes active as when we are executing that action (e.g., Fadiga, Fogassi, Pavesi, & Rizzolatti, 1995; Gallese & Lakoff, 2005). This mechanism allows us to track others' goals - the outcome to which their actions are directed - and to predict their movements. Sometimes, however, to successfully predict others' movements it is required that belief tracking informs goal ascription (Butterfill & Apperly, 2016). Take the example of Tom, who is sitting next to you on a plane and is getting ready to disembark. He is about to perform an action the outcome of which is to grasp his luggage. He falsely believes that it is is in the right-side compartment, whereas actually, the flight attendant moved it in the left-side compartment while he was at the restroom. If I ignore his false belief, then fixing only upon grasping the luggage as the goal of Tom's action would generate the wrong expectation of how his action would unfold, incorrectly predicting that he would move to the left-side compartment to reach and grasp his luggage (Butterfill & Apperly, 2016). In this case, I need to track Tom's belief to correctly identify the motor outcome of his action, which is that he would move to the empty right-side compartment to reach and grasp the luggage. In the current thesis, I review the literature on Action Understanding, a topic that has been tackled differently by researchers in the motor cognition field and researchers in the mindreading field, and I investigate through a series of experiments whether and to what extent motor processing and belief tracking are functionally related.

In Chapter 1, I provide an overview on the state of the art regarding the research in the field of human mindreading, which has yielded contradictory evidence and motivated competing theoretical accounts. Such overview is not to be intended as the starting point for an attempt of disentagleing all the contentious aspects that can be found in the mindreading literature, but rather it will serve as the foundation for understanding the two-systems account of mindreading (Apperly & Butterfill, 2009), which proposes the testable idea that the mindreading system might be functionally related to the motor system (Butterfill & Apperly, 2016). This proposition plays central role in the experimental work presented in this thesis.

In Chapter 2, I describe the motor systems in relation to the social world, focusing on how the discovery of Mirror Neurons, cells which fire both during the execution and observation of actions (di Pellegrino, Fadiga, Fogassi, Gallese, & Rizzolatti, 1992), has sparkled for decades, not without opponents, the interest in pursuing research aimed at a better understanding of how humans detect an action and ascribe goals, abilities that have been often grouped under the term ”Action Understanding” (Gallese, Fadiga, Fogassi, & Rizzolatti, 1996).

In Chapter 3, I start by arguing that mindreading and motor cognition are often considered separately and that their independence could be the result of experimental paradigms designed to isolate one process or the other rather than functional differences. Then, I discuss that we might advance our understanding of how observers efficiently process complex scenarios by integrating the progress that has been separately achieved in the two fields using tasks designed to focus on belief ascription and tasks focused on the kinematics of an action. Following the two-systems model of mindreading outlined by Butterfill, I proceed to explain how the motor system can carry information about the beliefs of another person to generate spontaneous and accurate behavioural expectations. I conclude by arguing that, if motor and belief-tracking processes are tightly integrated, interrupting their exchange of information would undermine the ability to predict the outcome of others' belief-based actions. Initial evidence in support of this conjecture is discussed.

In Part II, the experimental work I undertook is introduced. Here, I provide a description of the general methodology adopted in my experiments, which tested adults participants' belief-tracking and motor processes in real-life (Experiment 1A and Experiment 1B) and computerised (Experiment 2, Experiment 3A and Experiment 3B) interactive scenarios by analysing a combination of their explicit behaviour, eye-movements, body posture and hand movements. Throughout all the experiments, participants observed an agent storing an object inside box A. Then, while the agent was either present (i.e., True Belief condition) or away (i.e., False Belief condition), an experimenter transferred the object from box A to box B and then locked both boxes. Finally, in Experiment 1A, Experiment 1B and Experiment 2, the agent approached and unsuccessfully tried to open the empty box and participants had to help her by opening either the box she was directly struggling with or the full box. In Experiment 3A and 3B, participants did not spectate the agent attempting to open a box but were instructed to indicate the location of the object.

In Experiment 1A (Chapter 4), I describe the adaptation of the

Buttelman's helping task that I developed to study how motor and mindreading processes may be variously integrated in a real-life interactive scenario. Participants' eye-movements, body posture and final helping behaviour were analysed in Experiment 1A (and Experiment 1B). In Experiment 1B, a modification in the procedure was introduced to further refine the chain of events leading up to the agent unsuccessfully trying to open the empty box and to motivate participants in paying attention. In Experiment 2 (Chapter 5), a computerised version of a similar paradigm was adopted. Here, participants helped the agent by moving the mouse cursor and clicking on the empty box or on the full box. Experiment 2 crucially included a condition to test the prediction that bodily constraining an agent would disrupt observers' ability to motorically represent actions (as reflected by a lack of anticipatory body posture) as well as their mindreading abilities (as indicated by hand movement trajectories no longer attracted towards the belief-congruent location). In Experiment 3A and Experiment 3B (Chapter 6), two modifications were introduced to match more closely the procedure adopted by van der Wel, Sebanz, and Knoblich (2014) in what, as of today, is the only published mouse-tracker experiment testing spontaneous belief-tracking (with an additional go/no-go manipulation in Experiment 3B to ensure that participants visually perceived the agent). In particular, the helping component that characterised the first three experiments was dropped. The agent did not present any outcome-directed action after the belief induction phase and participants were simply instructed to click as fast as possible on the box containing the object. Further, the location of the response boxes was moved to the top corners of the screen to allow more time and space for the mouse cursor trajectories to reflect participant's online processing.

A general discussion of the current research and the implication for future research is laid out in Chapter 7.

Part I

Theoretical Background

Chapter 1

Mindreading

Everyday experience of the social world is supported by the ability to understand that other peoples' behaviour, as well as our own, is influenced by beliefs. When we are in the process of establishing whether or not another person has a false belief on how things actually are, we are making a contrast between our own knowledge and the accuracy of another person's belief (Wimmer & Perner, 1983). The ability to know facts about others' mental states such as beliefs, also dubbed mindreading, ultimately facilitates the prediction and interpretation of others' actions. Although there is agreement that mindreading plays a crucial role in shaping our social life, the same can't be said about the interpretation of how we come about to possess an adult-like understanding of mental states.

The longstanding debate about the developmental trajectory and the features characterising mindreading abilities largely depends on contradictory evidence emerging from false belief studies showing that 3-year-olds pass non-verbal, implicit, tasks but consistently fail verbal, explicit, tasks. In the next sections, I'll start with a description of the rationale behind the standard false-belief task, followed by an examination of the competing accounts that originated from its conflicting results.

1.1 False Belief reasoning

Mindreading is the process that allows an individual to come to know the contents of someone else's mental states such as her beliefs, desires or intentions. When we see a runner heading at full speed towards an iced portion of the walkway, we understand that her confident motion is governed by the false belief that the path is free from obstacles, and we can predict how the sequence of events is going to unfold without an external intervention. While researchers in the mindreading field agree that the understanding of others' belief-based actions is central in adults' interaction with the social world, the puzzling evidence emerging from infants' contradictory pattern of success in tasks requiring belief ascription, keeps the debate on the nature and developmental trajectory of mindreading open. As you may have noticed, by definition, beliefs are not the only mental states that we can access through mindreading. Yet, this section, as well as my entire discussion on mindreading, revolves around belief ascription. This choice is not a stylistic one but rather a practical one. In fact, since the provocative seminar "Does the Chimpanzee Have a Theory of Mind?" by Premack and Woodruff (1978), the surge in interest towards mental states ascription has been focused on how humans come to know another person's beliefs rather than other mental states. My point here, following Butterfill (2020), is that a practical way to understand mindreading is to understand the research on belief ascription.

1.2 Conceptual change and standard false-belief task

In Cognitive Psychology, conceptual change refers to a fundamental reconstruction of a theory through which we interpret the world: major changes in the core concepts result in modifications in related concepts and often lead to a change in the theory of reference (Inagaki, 2001). For example, it has been proposed that an early developing theory of mind based on perceptions and desires might conceptually change into a representational theory of mind incorporating beliefs (Gopnik & Wellman, 1994), or that the new ”representational” theory might extend (instead of replacing) an old ”situational” theory where mental states were construed according to the specific situation at hand (Perner, 1991).

In one of the most iconic studies in mindreading research, Wimmer and Perner (1983), set out to assess at what age children for the first time start to understand facts about others' beliefs. In their task, known as change-of-location task, children spectated a story similar to the following one: Maxi puts a chocolate bar in the left-side box. Then, Maxi goes to play outside and, in his absence, Mom moves the chocolate from the left-side box to the right-side box. Later Maxi returns. At this point, the researcher ask the children: ”Where will Maxi look for the chocolate?”

Typically, children older than 4 years correctly predict that Maxi will behave according to his false belief about the location of the chocolate by looking in the box where he last saw the chocolate (hereafter: now-empty box). On the contrary, children younger than 4 years display inability to understand another person's beliefs and to predict how Maxi will behave based on his beliefs: they fail this test by wrongly predicting that Maxi will look in the box containing the chocolate (hereafter: now-full box). Many variations of this now classic false belief task exist and they involve an unexpected transfer of all sorts of objects (e.g., marble, toy car), different protagonists (e.g., puppet, real actor) as well as modification in how the experimental question is asked (e.g., Where does maxi *think* instead of where will Maxi *look*) (see Baron-Cohen, Leslie, & Frith, 1985; Miller, 2004; Reidy, Ross, & Hunter, 2013 for examples of experiments using variations from the original change-of-location task). The change-of -location task is just one of the most commonly used false belief tasks.

Another well-known paradigm is the unexpected contents task. For instance, in the Smarties task (Perner, Leekam, & Wimmer, 1987) children are asked what they think is inside a Smarties box. Subjects answer "Smarties", only to find out that when the box is opened the content is, rather disappointingly, a pencil. Then, the pencil is put back in the box and a second child, unaware of the real content of the Smarties box, is brought inside the experimental room. At this point the subjects are asked to indicate what the second child think is in the box. Children older than 4 years tend to make an accurate attribution of the other individual's false belief about the content of the box while children around 3 years typically fail this task by indicating that the other individual thinks that the content of the box is a pencil. In yet another variation of the false belief task, children's failure in judging their own beliefs instead of someone else's also shows a similar age-related shift. Gopnik and Astington (1988) adapted an unexpected-identity task developed by Flavell, Flavell, and Green (1983) to show that not only younger children fail to understand that another person can have a different representation of the same object (e.g., Wimmer & Perner, 1983), but they also struggle in appreciating that their own representations can change over time. In their task, children were initially shown an object that was painted like a rock (a deceiving object that tricked adults as well), and then they were allowed to pick it up and squeeze it. After the children came to know that the object that looked like a rock was in fact a sponge, the authors asked them what they initially thought the object was. While older children pass the test by answering that they thought the object was a rock but now they know it is a sponge, 3-year-old children fail to understand that their current representation (i.e., ”it's a sponge”) was previously different (i.e., ”it's a rock”).

In conclusion, besides the commonly known False Belief tasks, a few of which I have discussed above, many other variations exist and, although there is some variability in their results, they typically come to the same conclusion that a conceptual shift occurs around 4 years of age. A case on point is a meta-analysis conducted on 178 studies (Wellman, Cross, & Watson, 2001), which found that correct performance in false belief tasks increases with increasing age and that the substantial age-related performance is not affected by other possible confounds such as type of tasks, nature of the objects, type of questions or differences in the protagonists, ultimately supporting the idea that children's mindreading abilities undergo a major conceptual change sometime between the ages of 2.5 and 5 years. Proponents of the conceptual-change view have described this pattern of results as a reflection of a discrete shift from a theory of mind based on perceptions and desires to a representational theory of mind incorporating beliefs (Gopnik & Wellman, 1994), or from an old ″situational″ theory where mental states are construed according to the specific situation that extend into a new ″representational″ theory (Perner, 1991), or from a simple understanding of desire as a need for something external (e.g., a chocolate bar) to a belief-desire psychology where the desirer's desire is compared to the actual content of the world (Wellman, 1990).

However, a contrasting account argues against the conceptual shift view and claims that young children's failure in traditional false-belief tasks reflect processing difficulties and that fully representational mindreading abilities are present, but masked, early in life if not since birth. For example, the ability to represent beliefs has been functionally associated with the ability to inhibit prepotent tendencies (for a meta-analysis, see Devine & Hughes, 2014). When young children are presented with a standard false-belief scenario, they come to hold two beliefs about the location of the object: their true-belief and the agent's false-belief. To successfully answer the test question (e.g., ″where will he look for the chocolate?″), children require the ability to select and attribute the false-belief by first inhibiting what in their experience is usually true (i.e., agents usually act under the guidance of true-beliefs) (Leslie & Polizzi, 1998). In the same vein, young children may fail the traditional change-of-location task because they are not able to inhibit their own prepotent knowledge about the true location of the object (Russell, Saltmarsh, & Hill, 1999). Thus, according to an early-competence view, traditional false-belief tasks are too complex and they end up detecting young children's processing difficulties (e.g., their lack of enough inhibitory power) rather than their lack of a representational system incorporating beliefs, which ultimately results in 2-3 years old failing the task. However, as a counter argument, it is difficult to interpret young children's poor performance by appealing to an excessive task complexity when children of the same age of those failing traditional false-belief tasks have no problem in processing information and in providing accurate verbal responses in tasks similar to false-belief tasks but that tap into their ability to attribute a different kind of mental states such as desires rather than beliefs (e.g., Gopnik & Slaughter, 1991). For example, in the "desire task" (Repacholi & Gopnik, 1997), preschool children observe an experimenter expressing disgust as she tastes one type of food (i.e., crackers) and happiness as she tastes another type of food (i.e., broccoli). When the experimenter places one hand, palm facing up, and requests some food, children offer the the food item that the experimenter likes but that they themselves don't desire. This task involves response selection and inhibition, and yet children pass this task from 18 months of age.

1.3 Early mindreading

As we have seen in the previous section, there is general agreement that children start providing verbal, explicit, evidence of belief reasoning sometime around the age of 4 years (Wellman et al., 2001). Nonetheless, efforts in the broader cognitive science shows that children can perform well in implicit tasks even before being able to understand or verbally explain what they are doing (e.g., Flavell, Speer, Green, August, & Whitehurst, 1981; Karmiloff-Smith, 1986). This motivated Clements and Perner (1994) to search for evidence that the explicit understanding of false belief as measured in traditional change-of-location tasks (e.g., Wimmer & Perner, 1983) might also be developmentally preceded by a different level (i.e., implicit) of false belief understanding. Here, the authors adopted a change-of-location story almost identical to the Maxi and the chocolate's one but, before asking the standard action prediction question (i.e., "which box will he open?"), the experimenter commented out loud "I wonder where he's going to look". The prompt was designed to elicit shifts in children's attention towards the location where they expected something to happen. While young children explicitly predicted that the other person was going to search in the box ultimately containing the object, their anticipatory looking behaviour revealed that they implicitly expected the other person to approach the box in which he falsely believed the object was located. Clements and Perner's data show that at about 2 years and 11 months, there is a dissociation between children's explicit and implicit predictions in a false-belief task. Clements and Perner argue that this contradictory patter of results supports the idea that, similarly to other cognitive domains, two separate types of knowledge underlies mindreading abilities: one that is explicit and verbalizable and a second one that is implicit and unverbalizable. While the former becomes available at about age 4 years and relies on the ability to judge (i.e., making a contrast between the information that I want to express and the reality of the facts), the latter is already present at least at age 2 years and 11 months and it only needs a representation of facts (without judgement) to trigger pure action (i.e., looking in anticipation of an event).

Anticipatory looking behaviour has been demonstrated in non verbal tasks with 2 years old (e.g., Southgate, Senju, & Csibra, 2007), 6-8 years old (Senju et al., 2010) as well as adults (e.g., Low & Watts, 2013; Senju, Southgate, White, & Frith, 2009). However, the interpretation of such results is not unanimous. While some authors warn that evidence on implicit understanding of false beliefs do not imply that young children possess fully developed mindreading abilities, which is something they achieve only after a conceptual change sometimes around the age of 4 years (e.g., Clements & Perner, 1994; Ruffman & Perner, 2005), exponents of early mindreading accounts claim that infants have a fully representational theory of mind by the second year of life, and some even suggest that it is innate (e.g., Leslie, 1987; Scott & Baillargeon, 2009) or emergent in the first few months of life (e.g., Luo, 2011).

The controversy surrounding the question of when children first come to understand others' mental states gained momentum with emergence of evidence drastically lowering the age at which children pass false belief tasks measuring implicit behaviour. In a groundbreaking paper, Onishi and Baillargeon (2005), exploited the natural tendency of infants to look longer at events violating their expectations (e.g., Woodward, 1998) to develop a violation-of-expectation (VOE) false-belief task, which allowed them to discover evidence suggesting that infants as young as 15-month-old possess false-belief understanding. Onishi and Baillargeon's task is similar to Wimmer and Perner's (1983) classic task but here, instead of asking a question, the authors let the infants watch until the end of the story. Initially, infants watch an agent handling a toy and then hiding it in a Green box on the infant's right as opposed to a Yellow box on the infant's left. Then, infants observed one belief-induction sequence, which resulted in the agent having either a true-belief (i.e., TB-Condition) or a false-belief (i.e., FB-condition) about the location of the toy. Finally, for half of the infants the agent reached into the Green box (i.e., Green-box condition) and, for the other half of the infants, she reached into the Yellow box (i.e., Yellow-box conditions). As the authors predicted, infants expected the agent to choose a box based on her belief about the location of the toy and infants looked longer when the agent acted in violation of such expectations. In the False-Belief condition infants looked longer when the agent searched the now-full box compared to when she searched the now-empty box; in the True-Belief condition infants looked longer when the agent searched the now-empty box compared to when she searched the now-full box.

Evidence in support of young children and infants' ability to pass false belief tasks has emerged from several studies exploiting anticipatory looking (e.g., Garnham & Ruffman, 2001; Southgate et al., 2007; Thoermer, Sodian, Vuori, Perst, & Kristen, 2012) and violation-of-expectation (e.g., He, Bolz, & Baillargeon, 2011; Kovacs, Teglas, & Endress, 2010; Surian, Caldi, & Sperber, 2007). Other studies, adopting a wide range of different paradigms and false belief scenarios, have also confirmed the same age trend, including evidence that children of 2.5 years of age display tense facial expressions (e.g., furrowed brow) when an agent with a false belief is about to be disappointed about the content of a box (Moll, Khalulyan, & Moffett, 2017), or that 6-month old children's neural correlates for action prediction become active when an agent falsely believes that a target ball is in the box but not when the agent falsely believes that the ball is not in the box (Southgate & Vernetti, 2014).

Furthermore, evidence in support of the early-competence claim also comes from real-time active-helping tasks (e.g., Buttelmann, Carpenter, & Tomasello, 2009; Buttelmann, Over, Carpenter, & Tomasello, 2014; Southgate, Chevallier, & Csibra, 2010). In particular, the task developed by Buttelmann et al. (2009) has largely inspired the methodology of my experimental work and, for this reason, it will be more extensively discussed in the Current Research Chapter (see pages 87-90). Here, I would like to alert the reader that Buttelmann and colleagues, using an interactive real-life variation of the classic change-of-location task, show that infants' helping behaviour seems to reflect an ability to represent others beliefs and goals. When an agent unsuccessfully tries to open a box in which she falsely believes the object is stored, 18-month-old actively move in the direction of the alternative box (i.e., the one actually containing the object). Buttelmann et al., suggests that 18-month-old understand that the agent represents the toy as being in the box she is trying to open so her goal must be to retrieve the toy. In the true-belief condition, when the agent unsuccessfully tries to open the box in which she knows the object is not stored, 18-month-old actively help by moving to open the box she is directly struggling with (i.e., the now-empty box). Buttelmann et al. explain that 18-month-old must reason that if the agent knows that the toy is in the other box, then she must have another reason for trying to open the now-empty box.

Conceptual-change accounts insist that young children's above-chance performance in nontraditional false-belief tasks does not demonstrate that they possess fully representational mindreading abilities. On the contrary, leaner non-mentalistic accounts can just as well explain the evidence. For example, infants in the VOE experiment by Onishi and Baillargeon (2005) might create expectations based on perceptual/behavioural rules without inferring mental states (Perner & Ruffman, 2005; Ruffman, 2014): infants learn that agents tend to look for objects where they last saw them and are surprised when an agent breaks this behavioural rule. Increased looking times might be the result of infants detecting a mismatch between the three-way association they encoded and remembered from earlier in the experiment (i.e., agent-object-location X) and the new three-way association shown in the behaviour of the agent during the inconsistent outcome in the test phase (i.e., agent-object-location Y). Furthermore, while Onishi and Baillargeon explain their results in terms of infants representing a mental state (agent *thinks* the object is at X), it is possible that infants only need to apply the agent's likely rule-based behaviour based on where he last saw the object. Finally, a similar lean interpretation, which however does not appeal to behavioural rules, suggests that Onishi and Baillargeon's results can be interpreted in terms of low-level novelty (e.g., Heyes, 2014a). Here, the low-level novelty account assumes that domain-general processes such as perception and attention are solely responsible for infants' looking times in false-belief tasks. The pattern of infants' looking time reflects discrepancies between the low-level properties of the stimuli that infants are exposed to during the early stages of the experiment (i.e., during the familiarisation and belief induction trials) and the low-level properties of the test stimuli. In fact, the reach into the Yellow-box event is more perceptually novel than the reach into the Green-box event given that during the familiarisation trials all the infants saw the agent-toy moving towards the Green-box.

1.4 Replication issues

As we have seen, several researchers advocate for a lean approach to results obtained in nontraditional false-belief tasks that have otherwise been interpreted as evidence in favour of the existence of rich and well developed mindreading abilities early in life. For others, however, since the VOE experiment by Onishi and Baillargeon (2005), the accumulation of evidence suggesting that infants and toddlers do in fact attribute false beliefs to agents, with more than 30 published reports adopting nontraditional tasks, has been "overwhelming", making it increasingly difficult to contemplate alternatives to the early-competence view (Scott & Baillargeon, 2017).

Such certainty about the reliability and meaning of results obtained in nontraditional false-belief tasks did not stay unchallenged for long. A wave of replication failures hit violation of expectation tasks (Dörrenberg, Rakoczy, & Liszkowski, 2018; Low & Edwards, 2018; Powell, Hobbs, Bardis, Carey, & Saxe, 2018), active-helping tasks (Crivello & Poulin-Dubois, 2018; Priewasser, Rafetseder, Gargitter, & Perner, 2018) and aticipatory looking tasks (Burnside, Ruel, Azar, & Poulin-Dubois, 2018; Dörrenberg et al., 2018; Grosse Wiesmann, Friederici, Disla, Steinbeis, & Singer, 2018; Kulke, Reiß, Krist, & Rakoczy, 2018) and was reported in a special issue of Cognitive Development (2018, vol.46). The challenge was a significant one, so much that some of the proponents of the existence of infants' rich mindreading abilities had their confidence admittedly shaken (Baillargeon, Buttelmann, & Southgate, 2018; Kampis, Kármán, Csibra, Southgate, & Hernik, 2021). In an invited commentary, Baillargeon, Buttlemann & Southgate (2018) addressed the issue and identified differences between studies as the main source of failures to replicate (see Table 1.1 for a summary of their interpretations).

Table 1.1: *Replication issue: summary of the interpretations provided by Baillargeon, Buttlemann & Southgate (2018) to explain failures to replicate the original Violation of Expectaion (VOE), Helping Task and Anticipatory Looking (AL) studies.*

Failed Replications due to:	**VOE**	**Helping Task**	**AL**
Procedure	•	•	
Familiarity Bias	•	•	
Sample Characteristics	•	•	
Statistical Power		•	•
Inclusion Criteria			•

For example, Baillargeon et al. (2018) describes the negative VOE findings reported in Powell et al. (2018) as the result of changes introduced in the familiarisation and test trials which ultimately confused infants and/or did not allow for enough time to generate expectations. Using a VOE paradigm to test the same infants multiple times (Yott & Poulin-Dubois, 2016) might instead introduce a memory confound leading to contaminated results. Baillargeon et al. are also skeptical of studies comparing adults' judgements on the expectedness of VOE scenarios and infants anticipatory looking performance (Low & Edwards, 2018), arguing that tasks suitable for infants might not be suitable for adults given that the latter are better in generating explanations and rely on a greater knowledge when perceiving the experimental stimuli.

Similarly, with respect to the original active-helping tasks' results, Buttlemann identifies several critical aspects characterising the replication studies reported in the special issue of Cognitive Development. First, differences in procedure, materials and apparatus might explain the results obtained by Crivello and Poulin-Dubois (2018) and Priewasser et al. (2018). For example, having the infants sitting at a table close to the boxes, as opposed to sitting on the floor at a larger distance as in the original paradigm, drastically reduces the timing of the events and might result in not enough time for the infants to process the stimuli. Second, while the original study consisted of one single task, infants in Crivello and Poulin-Dubois (2018) were tested using a battery of four tasks in which the agent was always the same: Buttleman argues that a decrease in mindreading activity might be the result of an increase in familiarity with the agent. Third, while the original Buttelmann et al. (2009) tested German children, Crivello and Poulin-Dubois (2018) tested Canadian children and Priewasser et al. (2018) tested Austrian and Scottish children: samples with a different cultural background might be characterised with a different level of mastering an interactive helping scenario. Strangely, Buttleman cites Wellman et al. (2001) to support this argument even though the stance taken by Wellman on the cultural influence on mindreading is in contrast with Buttleman's ("...young children in Europe, North America, South America, East Asia, Australia, and Africa [...] all acquire these insights on roughly the same developmental trajectory."; Wellman et al., 2001 p. 679). Lastly, Buttelman emphasises that the failed replications lack statistical power because of their smaller sample size compared to the original study, which included a total of twenty-five 18-month-olds infants in the crucial false-belief condition. However, against the 25 participants assigned to the false-belief condition in the original study, Crivello and Poulin-Dubois (2018) had a final sample of forty-one 18-month-olds infants and Priewasser et al. (2018) included a total of thirty-three 18-to 32-month-olds infants (between study 1 and study 2) performing the original false-belief helping task .

Sample size is a topic that Southgate also discusses in her interpretation (Baillargeon et al., 2018) of failures to replicate her original anticipatory looking study (Southgate et al., 2007). For instance, by applying the same inclusion criteria as the original study, only 9 participants in Kulke et al. (2018) passed the familiarisation trials and were tested in the False-Belief scenario. However, while Southgate does encourage replication attempts to adhere to the original methodology, and criticises studies (e.g., Dörrenberg et al., 2018) that fail to do so (Baillargeon et al., 2018), she also reports her own failure in replicating the original anticipatory looking results (Kampis et al., 2021). Further, motivated by her failed replication and by the wide variety of performance thus far reported (from poor to perfect) she concludes that this paradigm does not reliably measure anticipatory looking behaviour and is therefore not suitable to investigate false belief understanding in 2-year-olds.

All in all, the large amount of evidence thus far collected in support of the view that rich mentalizing is present early in life is increasingly matched by an equally substantial number of failed replications. In lieu of such conflicting evidence, caution towards rich interpretations and open-mindedness towards alternative theoretical explanations have been warranted (Poulin-Dubois et al., 2018). Such moderate approach is shared by some proponents of the rich mentalizing account, who question the reliability of paradigms used to test infants and convene that we are currently in a position to neither exclude nor confirm that infants possess rich mindreading abilities (Kampis et al., 2021).

1.5 Two-Systems account

As I have discussed in the sections above, despite the large amount of evidence gathered from different false belief tasks and measures, there is still a general lack of consensus on which theoretical framework, from nonmentalistic beginnings with conceptual-change to rich nativism, best explain the puzzling results. In this section, I take into consideration another alternative account: The Two-Systems theory of mindreading (Apperly & Butterfill, 2009; Butterfill & Apperly, 2016; Fizke, Butterfill, van de Loo, Reindl, & Rakoczy, 2017; Low, Apperly, Butterfill, & Rakoczy, 2016). Here the proposition is that the pattern that has been so far interpreted as a series of contradictory results, with infants appearing to be sensible to someone else's mental states in some tasks but not in others, might in fact underlie the existence of 2 distinct systems for mindreading: a late-developing flexible system and an early-developing efficient system.

The flexible system represents beliefs and other propositional attitudes as such, it is late-developing and relies on cognitively demanding reasoning processes. That is, humans come to posses an adult-like ability to reason about beliefs in an abstract fashion through a gradual developmental process that is linked to the trajectory of other cognitive and social domains such as language, executive function and parent-child interactions (e.g., Astington & Baird, 2005; Perner, 1998) and that will ultimately support the emergence of an ability to flexibly take into account all the known facts in support of explicit reasoning about beliefs. However, generating and monitoring complex causal structures to support propositional attitudes is not something that can be done automatically and comes at a high cognitive cost. For instance, when adults are unexpectedly asked to reason about an agent's belief about the location of an object, after a sequence of events has already ended, they need to retroactively retrieve information that they didn't automatically encode, which ultimately result in a response that is slower compared to the one they can provide to questions about information that they had automatically processed, such as the real location of the object. On the contrary, if the agent's belief state is salient from the beginning of the sequence (that is, if adults are instructed to keep it tracked), the time taken to answer questions about beliefs and questions about reality is the same (Apperly, Riggs, Simpson, Chiavarino, & Samson, 2006).

However, there is also evidence suggesting that belief tracking can occur automatically. For instance, adults are slower in detecting the location of an object when an agent has a false belief about its location even though the agent's belief state is completely irrelevant to the task (Kovacs et al., 2010). So, how do we overcome conflicting evidence on the automaticity of mindreading? And how can we explain that fluent everyday interactions require mindreading to be fast and effective although, as adults, we often strategically plan what to say or do based on the belief and knowledge state of our interlocutors? And how do we find a solution to the seemingly contradictory evidence showing that infants pass some false beliefs tests but fail to declare and justify an accurate judgement in a flexible fashion until the age of 4 years? As hinted at the beginning of this section, while opposing views have approached these contradictions by appealing to either rich or lean interpretations, here the idea is that such contradictions might be so only by name and that they might be resolved if we think about the adult's mindreading system as the result of the late-developing flexible system, working in parallel with a second, early-developing, efficient system.

The efficient (or minimal) system represents belief-like states (i.e. registrations) instead of belief states as such. Registrations are relations between an agent, an object, and a location. Butterfill and Apperly (2013) define that an agent registers an object and a location if the agent recently encountered it and that location. Aimed with this principle, the efficient system can predict the successful or unsuccessful actions of an agent who has or has not correctly registered the object whereabouts. The efficient system is early-developing and it trades flexibility in exchange for speed and automaticity. The low demands that the efficient system puts on the cognitive system allow adults and children, but also infants, to track, within limits, belief-like states. And the limits of the efficient system are a crucial aspect of the two-systems theory of mindreading.

1.5.1 Signature Limits

In certain situations it is possible to generate the same expectations by explicitly reasoning about beliefs (e.g., ”Maxi falsely believes *that* the chocolate is in the left box”) or by automatically tracking belief-like states (e.g., Maxi-object-left box). In order to tell which system is being used, and to test the existence of a minimal system, we need to put aside mindreading tasks that can be equally interpreted by resorting to the flexible system or the efficient system. Instead, the focus has to be on tasks in which the efficient system makes peculiar and consistent mistakes, that is, tasks in which there is evidence of signature limits (i.e., a set of incorrect predictions derivable from one specific system and not from other systems under consideration). In other words, if adults and infants pass the same task, they could do so for a different number of reasons but, if they both fail in a very specific way, it would mean that they processed the information using the same system of reference and that that system failed (Butterfill, 2020; Low & Watts, 2013).

Given that the efficient system relies on registrations to represent belief-like states, Butterfill and Apperly (2013) propose the conjecture that registrations cannot represent aspectuality (i.e., they do not distinguish the different aspects under which the same object can be represented). A testable prediction would be that adults and infants' performance in false belief tasks involving numerical identity is subject to signature limits. Just as an example, a false belief about numerical identity is the one that Lois Lane has regarding Clark Kent's alias Superman. Sitting comfortably at the movie theatre, spectators are well aware that Lois acts and thinks according to her false belief that Clark and Superman are two distinct identities belonging to two distinct persons, while they know that the same individual holds both the two identities. So, when Lois witnesses Clark entering a red building and later she sees Superman flying out of it and entering a yellow building, spectators can flexibly reason that ”Lois will look for Clark inside the red building because she believes that Clark and Superman are two different persons and that Clark never left”. However, following Butterfill and Apperly’s (2013) conjecture, if we were to measure the spectators’ fast and automatic expectations about where Lois will look for Clark, we should find that their efficient system makes the wrong prediction that Lois will look inside the yellow building. This would happen because, in capturing registrations as mere relational states that connect an agent to a referent and a location (e.g., Lois-Clark-red building), it cannot accommodate the different aspects (e.g., identities) by which the agent might represent that single referent. The efficient system will treat Clark and Superman as a single individual (who left the red building). Evidence obtained using different scenarios involving numerical identity seems to support this conjecture (e.g., Edwards & Low, 2017; Fizke et al., 2017; Low, Drummond, Walmsley, & Wang, 2014; Low & Watts, 2013; Wang, Hadi, & Low, 2015).

For instance, Low and Watts (2013) presented children and adults participants with a scene in which an agent observes a preferred *blue* toy robot moving from one box (i.e., Box A) to a second box (i.e., Box B). Unbeknownst to the agent, the robot is *blue* on one side but *red* on the other side. Within Box B, the robot secretly turns around side to side, and then it moves back inside Box A while facing the *red* side towards the agent. At this point, like Lois Lane, the agent believes that there are two separate entities: the *blue* robot that he prefers to retrieve and a *red* robot. On the contrary, thanks to an aperture on one side of Box B, participants spectated the robot turning around and so they know that only one double-coloured robot exists (see Figure 1.1 for a simplified representation of the setting).

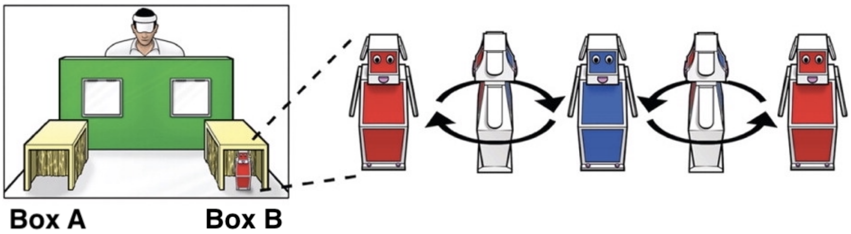


Figure 1.1: ***Low and Watts (2013): experimental setting.*** *Simplified representation of the setting and the dual-identity robot adopted by the authors. While the agent can't see the double-coloured robot turning around, participants have full visual access on the inside of the box.*

Can participants reason about where the agent will look for the preferred *blue* robot based on her false beliefs about the number of robots? Can they generate automatic and accurate anticipations as well? Fitting with Butterfill and Apperly's (2013) theorizing, participants older than 4 years of age were able to provide accurate verbal predictions that the agent would look for the desired *blue* robot where he falsely believed it was located (that is, inside the now-empty Box B). However, both children and adults' automatic anticipatory looking revealed that they generated the wrong expectation that the agent would search the actual location of the robot.

Evidence obtained using different measures also supports the conjecture that humans possess an efficient mindreading system that is subject to limits in the kind of information that can process. For instance, Fizke et al. (2017) developed 2 experiments to test signature limits in toddlers' understanding of false belief as indicated in their active helping behaviour. Similar to the original findings by Buttelmann et al. (2009), 2- and 3-year-olds took into consideration the agent's belief about the location of an object (e.g., concerning a rabbit that is transformed into a carrot) when choosing their active helping behaviour. However, when the agent's belief involved the aspectuality of an object rather than its location, toddlers did not choose to help based on the agent's belief.

Further, the contrasting results obtained between Level-1 and Level-2 visual perspective-taking tasks (cf. Flavell, Everett, Croft, & Flavell, 1981) have also been interpreted in terms of mindreading efficiency, with the former being associated with the efficient and automatic system and the latter with the flexible and non-automatic system (e.g., Apperly & Butterfill, 2009; Edwards & Low, 2019; Surtees, Butterfill, & Apperly, 2012). In Level-1 tasks, participant and agent see the same or a different number of objects because some of the objects that are visible to one may not be visible to the other one. For example, when adults are asked how many things they can see in a scene, they are faster and more accurate if they see the same number of dots as the agent in the scene (e.g., Furlanetto, Becchio, Samson, & Apperly, 2016; Qureshi, Apperly, & Samson, 2010; Samson, Apperly, Braithwaite, Andrews, & Bodley Scott, 2010). And a conceptually similar effect is present in infants as well (Brezack, Meyer, & Woodward, 2021; Luo & Baillargeon, 2007; Sodian, Thoermer, & Metz, 2007). The fact that this pattern of results is observed when participants are not required to track what the agent sees suggests that adults and infants track the agent's line of sight automatically. On the contrary, in Level-2 tasks, participant and agent see the same object but under different aspects because the object is seen as something from the participant's point of view and as something else from the agent's point of view. For example, when children and adults sit at a table facing an agent, they respond with the same speed to the numeral "8" compared to the numeral "6", which suggests that adults and infants do not automatically compute the different aspect under which someone else can perceive the same entity (that is, that the numeral "6" is actually "9" from the agent's point of view) (Surtees et al., 2012). Therefore, in line with Apperly and Butterfill's (2009) theorizing, efficient mindreading seems to accommodate situations in which an agent does not see an object that the observer can see (i.e., level-1 perspective-taking) but not situations in which an agent and the observer are appreciating different aspects of the same object (i.e., level-2 perspective-taking).

Of course, the validity of the 2-systems account's interpretation of results obtained in level 1/2 and identity tasks is debated. For example, some argue that a leaner submentalizing approach is better suited to explain the results obtained in the visual perspective tasks. Under this lens, Level-1 perspective taking do not require a mental representation of another person's field of view (as supported, for instance, by Apperly (2010)), but can be explained in terms of low-level confounders such as cueing effects (e.g., Heyes, 2014b; Santiesteban, Catmur, Hopkins, Bird, & Heyes, 2014). Others claim that, since some identity tasks involve rotating objects (e.g., Low et al., 2014; Low & Watts, 2013), they are more cognitively demanding compared to location tasks. As a consequence, Low and colleagues' results may not speak to the ability, or rather the lack of ability, to automatically represent the different aspects under which an object can be represented. Instead, data on signature limits reflect the high working memory demands required to visually rotate an object (Carruthers, 2016). For instance, some authors show that, by lowering processing demands and adopting identity tasks that do not involve rotating objects, it is possible to observe putative mindreading abilities in infants (Scott & Baillargeon, 2009; Scott, Richman, & Baillargeon, 2015). However, others provide more parsimonious interpretation of such evidence (e.g., Butterfill & Apperly, 2013; Low & Edwards, 2018) and find that signature limits emerge also in tasks not involving mental rotation (e.g., Fizke et al., 2017; Oktay-Gür & Rakoczy, 2017).

Although attention is warranted when interpreting specific results, initial evidence on the existence of signature limits supports the idea, or at least motivates research in this direction, that minimal mindreading operates with a relative degree of automaticity and is restricted in the kind of information that it accommodates. Nonetheless, a theory of minimal mindreading also requires incorporating the possibility that goal ascription can be achieved in a cognitively efficient manner (Butterfill & Apperly, 2016; Michael & Christensen, 2016). Fortunately, goal attribution plays a crucial role in the 2 systems theory: the functioning of an observer's efficient system is theoretically grounded on the principle that is possible to represent goals without the need of appealing to mental states such as beliefs or intentions and that goals allow agents to engage in purposive actions directed towards objects that they have encountered and registered.

1.5.2 Goal ascription

Understanding actions is essential for understanding the social world, and the kind of mindreading I have been discussing is tightly linked to agents performing actions. An action can be described in terms of its kinematics, goals and intentions. For example, let's take into consideration the act of grabbing a knife. Once you have visually encountered and registered the knife being on the kitchen table, you initiate a series of finely tuned body displacements which are characterised by specific timing, speed and force that best allow you to achieve the goal of grasping the knife and ultimately fulfil the distal intention of chopping an onion. However, if your goal is to grasp a knife that is oriented with the handle towards you, you will prepare and execute a reach-to-grasp action whose kinematics will be different compared to when the blade, instead of the handle, is facing you. In the same vein, the kinematics of your action will be different when your goal is to push aside the knife instead of grasping it, and they will also be different when the goal of grasping stays the same but your intention is not to chop an onion but to stab an intruder.

The above example conveys an idea of how goals can feature in purposive action, and I'll talk more about the characteristics of action and action observation in the next chapter. For now, it is important for me to be clear that when talking about the goal of an action I am talking about the outcomes to which that action is directed and when talking about goal ascription I'm referring to the process of identifying an outcome to which an observed or anticipated sequence of bodily configurations and joint displacements are directed (Butterfill & Apperly, 2016; Sinigaglia & Butterfill, 2016). Crucially, goals are not intentions nor other mental states and the question that needs to be answered is whether goal ascription can ever be achieved, in a cognitively efficient manner, without knowing the ultimate intentions or other mental states that motivate the observed action.

1.5.2.1 Infants ascribe goals

A large body of research provides evidence that infants ascribe goals when observing an action. For example, Woodward (1998) reported that 6 to 9-month-old infants are sensitive to the goals of an agent performing an action aimed at grasping one toy out of two. In this study, infants were first habituated to an agent reaching for a teddy bear instead of a ball. In the test trial, the locations of the toys were swapped and the agent reached either for the teddy bear at the new location, or for the ball at the old location. Infants looked longer when the agent reached for the ball, suggesting that the goal they ascribed to the action (observed during the habituation phase) was to reach the object rather than reaching the location, and that they expected the reaching action observed during the test trial to have the same goal.

A stronger test of whether infants can generate action predictions based on goals, instead of analysing the goal structure of already concluded actions, comes from variations of the original Woodward (1998) study. For example, Cannon and Woodward (2012) measured anticipatory eye movements to support the idea that infants not only represent actions as goal-directed, but they also use this information to generate anticipatory predictions about an agent's action when the context (i.e., the location of the objects) is changed. Other studies, using both looking times (Luo & Baillargeon, 2007) and anticipatory looking (Kim & Song, 2015), have also reported that infants generate goal expectations taking into account the agent's visual access of the objects that are present on the scene. If the agent can see two objects and decide to interact with a particular one during the familiarization, infants will predict that she will prefer to reach the same object in the test phase. However, if visual constraints allow the agent to see and interact with only one object out of two objects during the familiarization phase, the infants will not be able to predict which object the actor will prefer to reach when both objects become visible in the test trial (Kim & Song, 2015) (see Figure 1.2 for a visual representation of the conditions and results).

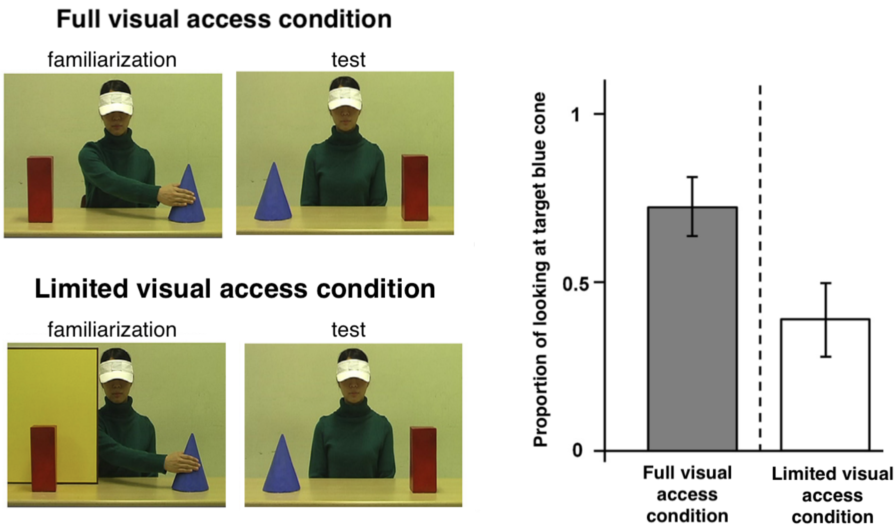


Figure 1.2: ***Kim and Song (2015)***: *video stills of the Full vision condition and the Limited vision condition presented together with infants' mean proportion of time looking in anticipation towards the goal object (i.e., blue cone) (adapted from Kim and Song (2015)).*

Beside being able to ascribe goals to the actions performed by someone else, there is no doubt that adults can also provide rich explanations about the hidden mental states that are fuelling such actions. For example, if I see a man pre-shaping his hand and extending his arm in the direction of a beautiful wild flower growing in a field, I can quickly track that his joint displacements are directed to the outcome of picking that flower. In addition, I might also reason that, since today is Valentine's day, his intention could be to gift the flower to a loved one with the desire of making her happy. But the man looks rather agitated. Maybe his love is not returned, which might also explain the excessive use of cologne that I can smell from the opposite side of the road.

The number of possible intentions, desires or beliefs hiding behind a series of joint displacements aimed towards an object are countless, and someone with the time and cognitive resources could explore them one by one. However, while adults certainly possess the ability to integrate goal ascription with mentalistic interpretations of the social world, it is unclear whether infants can do the same. Some authors think they do, and provide rich interpretations of results showing that infant ascribe goals to observed actions (e.g., Cannon & Woodward, 2012; Kim & Song, 2015; Woodward, 1998). But the question here is whether such rich mentalizing activity is necessary for goal ascription or whether, in a limited but useful number of situations, it's possible to ascribe goals to simple actions in a cognitively efficient way (that is, without requiring information about mental states).

1.5.2.2 Teleological interpretation of goal ascription

Csibra and Gergely (1998) have argued that the adult-like and mentalistic way of interpreting actions is an extension of an earlier developing, nonmentalistic, teleological stance of interpretation. Under this theoretical framework, infants can ascribe goals to purposive actions by identifying a relation between the action, the goal state, and the constraints. And they do so by adopting the principle of rational action whereby an action can be explained in terms of a goal state if, and only if, it is perceived as the best action to undertake when achieving that goal given the situational constrains. Crucially, a teleological interpretation of an action is achieved without accessing beliefs, intentions or desires.

There is converging evidence showing that the teleological stance underpins infants' ability to track goals during action observation (for a review see Gergely and Csibra (2003)). For example, in a study by Gergely, Nádasdy, Csibra, and Bíró (1995), infants are habituated to an event in which a small ball approaches a large ball by jumping over an obstacle that is laying on its path. When the obstacle is removed, infants look longer (that is, they are surprised) if the small ball repeats the (now inefficient) jumping trajectory compared to when it moves on a (now efficient) straight line (see Figure 1.3). According to the principle of rational action, it is initially possible to interpret the act of jumping across the obstacle in terms of the goal of approaching the larger ball: jumping is the best way to achieve that goal considering the physical constrain posed by the obstacle. Once the obstacle is removed, infants still expect the action to unfold in the most efficient way to achieve the same goal of approaching the ball, which now would be on a straight line, and they are surprised (i.e., looked longer) when the moving ball maintains a bouncing trajectory because it is inconsistent with the principle of rational actions.

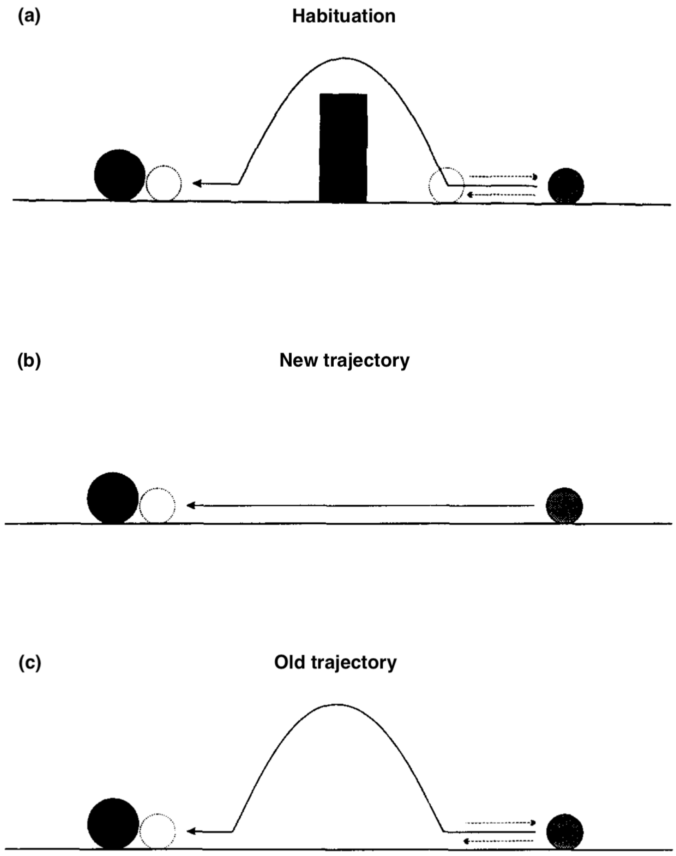


Figure 1.3: ***Gergely, Nádasdy, Csibra, and Bíró (1995)****: habituation and test events. (a) in the habituation phase the small ball moves forward and back to the starting position one time and then starts again towards the big circle but this time jumping across the obstacle. (b) The small ball approaches the large one through the shortest straight pathway. (c) The small ball approaches the large one through the old and now inefficient trajectory (adapted from Gergely, Nádasdy, Csibra, and Bíró (1995)).*

The issue with teleology is that it doesn't allow for accurate goal ascription when the observed action fails. For example, if I'm sitting at the pub with a friend and I see his hand starting to open up and his arm starting to move forward, among the possible outcomes of his initial movements (e.g., picking up a napkin, grasping his or my pint of beer, checking the phone and so on), I can ascribe at a certain point the goal of his action to be to reach and grasp his pint of beer. According to the teleological stance, I can do so whenever the kinematics of his unfolding action are the best way of reaching that, and only that, particular outcome. The ”only that” part is critical for teleology. In fact, in a scenario in which the speed of my friend’s arm is few millimeters per second too fast and he ends up knocking down the glass of beer, the teleological stance would generate wrong predictions. Under the teleological stance, as soon as my friend starts to move, a wide range of outcomes can be considered as the actual goal of his action. The more my friend’s hand gets closer to the glass of beer, the more goals unrelated with the glass of beer (e.g., checking the phone) are excluded from being the actual goal of the action. Finally, when my friend ends up knocking down the glass, goals unrelated with knocking down the glass (e.g., grasping the glass) are also excluded as the actual goal of his actions. In a situation like this the teleological stance would therefore wrongly predict that grasping the pint of beer was not the goal of my friend’s actions and that the goal of knocking down is the actual goal.

1.5.2.3 Statistical interpretation of goal ascription

While the teleological stance is sufficiently adequate to describe a range of situations in which successful goal ascription occurs, there are also cases in which the observer makes use of statistical regularities to interpret an action (Ruffman, Taumoepeau, & Perkins, 2012). Let's consider the case of a teenager who is grounded at home during a hot summer morning. He knows that mom will exit the house in order to go to work at 8 a.m., and he is not planning on missing the daily bike ride with his friends. At 7:55 mom finishes her coffee and starts to move: the young boy predicts that she will be out of the house by 8 a.m., as per her regular schedule. In predicting her action of exiting the house, the boy doesn't need to track other subsidiary actions that mom takes before going out. For example, he doesn't need to track that she reaches into the purse with the goal of grabbing the car keys, or that she will spend few extra seconds to gently kick the doormat that is out of position. What matters for the boy is that he can accurately predict his mom's relevant action based on her routine (i.e., based on the statistical regularity of her leaving the house at 8 a.m. each morning).

While there is empirical evidence that infants sometimes use teleological reasoning to understand action (e.g., Gergely et al., 1995), there are also studies showing that sometimes they rely on statistical regularities (e.g., Paulus et al., 2011). For example, Paulus et al. (2011) measured infants and adults' anticipatory looking to investigate whether action prediction is supported by statistical learning or teleological reasoning. Participants were habituated to an agent starting to move along a path, disappearing under an occluder and then appearing again to continue the motion via the longer but more efficient path, as opposed as via the shorter, but obstructed, path. In the test phase, the obstacle was removed. At this point, the agent could take both paths. However, now the most efficient way to reach the goal location is via the short and unobstructed path. If participants use teleological reasoning to anticipate the agent's action, they should anticipate (by means of anticipatory looking behaviour) that the agent will choose the best way available to fullfill his goal of reaching the end location. That is, they will expect the agent to take the short path. On the contrary, the results show that participants still expect the agent to take the longer path, which support the view that sometimes observers rely on previously acquired information to predict the outcomes of an upcoming action.

1.5.2.4 Motor interpretation of goal ascription

In the attempt to describe how goal ascription can be achieved in a cognitively efficient manner, without making inferences about mental states, we faced results suggesting that onlookers sometimes interpret an observed actions on the basis of statistical regularities whereas other times their predictions are in line with a teleological stance. At this stage, teleology seems to provide us with an adequate description of how goal ascription can be achieved efficiently, but the predictions that it generates are not always accurate.

The evidence on how goal ascription is achieved points in different directions and, in the sections above, I discussed that sometimes infants seem to use statistical regularities when interpreting an action and some other times they seem to use teleological reasoning. Another theory, which became popular after the discovery of mirror neurons in the late 80's (Rizzolatti et al., 1988), postulates that goal ascription and action understanding is achieved by representing the observed action motorically (Rizzolatti, Fogassi, & Gallese, 2001): while motor representations characteristically guide the execution of an action, they are also involved when observing someone else performing the same action. Motor representations would allow to translate an action into a coding that is familiar to the observer and that ultimately facilitate fast goal tracking and action understanding, independently from knowledge of the agent's mental states.

But what is a motor representation of an action? I shall talk more in detail about motor representations in the next chapter but here, in an attempt to make things easier, let us try to draw some parallels with a more popular kind of representation, the pictorial representation of a sunset. The pictorial representation displays a multitude of features which, taken together, provides a version of reality as appearing to the eyes, or imagination, of the painter. Based on the expertise of the painter, the representation portrayed on canvas will be more or less accurate, but it will certainly have distinctive features that makes it clear enough for him and for the buyer of what the portrayed subject is: there is an abundant use of orangish colours, a semicircle on the background is intersected by a straight line that goes from one side of the paint to the other side and so on. Similarly, a motor representation of a goal-oriented action (e.g., grasping a ball) is a kind of representation in which the portrayed subject is the action, which is depicted (that is, represented) in terms of action-related features, such as speed, force, orientation and type of limb required. A motor representation within the observer will ensure that, often enough, outcomes represented motorically are actually goals of the action. In this way, goal ascription can be achieved in a cognitively efficient way whereby the only representations are motor representations (Sinigaglia & Butterfill, 2016).

And, similar to your ability to sketch a tree just by imagining a tree (that is, in the absence of an object perceived through your senses), motor representations of an action also become active when you think about that action (e.g., Filimon, Nelson, Hagler, & Sereno, 2007; Jeannerod, 2006; Szameitat, Shen, & Sterr, 2007; Zwaan, van der Stoep, Guadalupe, & Bouwmeester, 2012). Against this background, Butterfill and Apperly (2016) propose the theoretical conjecture that when observing an agent, the observer's motor system may generate expectations by taking into account not only facts about the actual environment but also facts about the environment as specified by the agent's belief or belief-like state.

Chapter 2

Motor Cognition

Social life is an essential part of the human experience and actions are the primary means by which humans interact with each other and the objects around them. To survive and thrive in the surrounding world we need to know how to perform an action and to recognise and understand someone else's actions. In the previous chapter, I discussed how action observation and understanding have been approached in the Mindreading field, which has largely focused on experimental tasks designed to investigate mental representations underpinning observers' tracking or reasoning about another person's belief-based behaviour. While informative, such tasks tend to neglect potential activations in participants' own motor system that can be revelatory of observers' rapid online action understanding. However, in recent years, Butterfill and Apperly (2016) have conjectured that the efficient (or minimal) mindreading system might turn out to be an efficient motor-reading system: an observer's motor system generates fast and automatic prediction by taking into account not only facts about the actual environment but also facts about the environment as specified by the agent's belief-like state. The conjecture provided motivation for my experimental work to investigate whether belief-tracking could map onto or modulate motorically grounded expectations about the goals to which an agent's actions are likely to be directed. However, in trying to bridge the gap between the mindreading field and the motor cognition field, we are still missing an adequate description of how the study of action observation and understanding has been approached in the motor arena.

The focus of this chapter is on a line of research in the motor cognition field that, since the discovery of the mirror neurons, has suggested, not without criticism (for a review, see Gallese, Gernsbacher, Heyes, Hickok, and Iacoboni, 2011), that the peculiar pattern of activation of an observer's motor system allows the understanding of another person's actions without needing inferential processing. In the following sections I begin by describing the properties of the mirror neurons, focusing on their role in action understanding.

2.1 The Mirror System

The environment has many objects and movements. Recognising and understanding an action among these stimuli is crucial for surviving and the ability to achieve a motor representation of an action and to use it for future behaviour (that is, action understanding) is necessary for social interaction (Rizzolatti et al., 2001). Direct evidence reveals that in the premotor cortex of non-human primates there is a category of cortical cells, named mirror neurons, which becomes active not only when performing a particular action but also when observing a similar action (di Pellegrino et al., 1992). Later, the use of indirect techniques such as Transcranial Magnetic Stimulation (TMS) and functional Magnetic Resonance Imaging (fMRI) has revealed that a similar system for action understanding exists in humans as well (e.g., Fadiga et al., 1995).

2.1.1 The discovery of mirror neurons

Mirror neurons are a particular category of visuomotor cortical cells that were firstly discovered in the monkey's ventral premotor cortex through the direct application of electrodes in area F5 (Rizzolatti et al., 1988). There are two classes of visuomotor neurons in F5: canonical neurons respond to the presentation of an object; mirror neurons become active when the monkey performs an action as well as when the monkey observes a similar object-directed action (Rizzolatti & Luppino, 2001). However, an action performed by someone else does not necessarily need to be visually accessible for it to evoke a mirror response. For instance, both the kinematics and the sound of a motor act are able to activate mirror neurons, as long as the goal is available (Kohler et al., 2002; Umiltà et al., 2001). Kohler et al. (2002) found that a portion of mirror neurons in F5 not only discharges when the monkey performs or observes an action, but also when the monkey hears a sound related to that action (e.g., the sound of ripping a paper). The same neuron that becomes active when the monkey observes the act of ripping a paper also discharges when the action is visually occluded but the characteristic ripping sound is still available (but it does not become active following a white sound). Along the same vein, Umiltà et al. (2001) found that mirror neurons discharged when the ending part of a goal-directed hand movement was hidden from the observing monkey's point of view: if the monkey registered that an object was hidden behind an occluder, a portion of those neurons discharging in a full-vision condition also fired when the hand action was directed towards a hidden object (see Fig. 2.1 for an example of a single neuron responding to action observation in full vision and partially hidden vision).

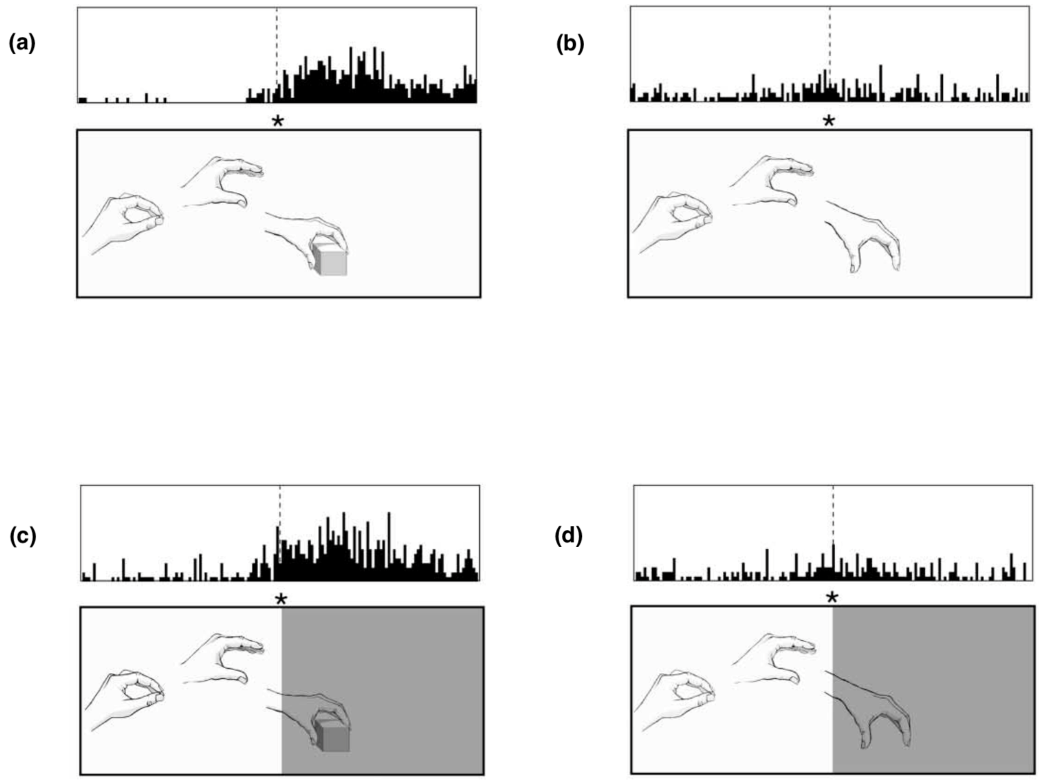


Figure 2.1: ***Umiltà et al. (2001): Neural Response in Full and Hidden Condition.*** *The experimenter reached and grasped an object in (a) and (c), or mimed grasping in (b) and (d). The monkey saw the whole action in (a) and (b) but only the initial part of the action in (c) and (d). The monkey was habituated to the object being present or not. Histograms represent the amount of neuron activation, aligned with the hand crossing a stationary marker (indicated in the picture with an asterisk). (adapted from from Umiltà et al., 2001).*

Mirror neurons also present a large degree of generalization. For example, their activation does not depend on the distance between the action and the observer, the same mirror neuron that responds to a human hand grasping an object also fires when the grasping hand is the one of a monkey, and some of them fire with the same intensity regardless the hidden meaning of the object (grasping a piece of food versus a geometrical object) (Rizzolatti & Craighero, 2004).

From this evidence, it appears that mirror neuron activity reflects general characteristics of the action, like the outcome to which an action is directed. The ability of the mirror neurons to discharge when the low-level information about an action is not fully available or is different from when the observer is the actual agent (for example, in terms of distance from the object) would allow for goal ascription in situations where the access to features defining a particular action are limited, ultimately leading to understanding a perceived action. It has indeed been proposed that, by decoding information into knowledge, the functional role of mirror neurons is to facilitate action understanding (Rizzolatti et al., 2001).

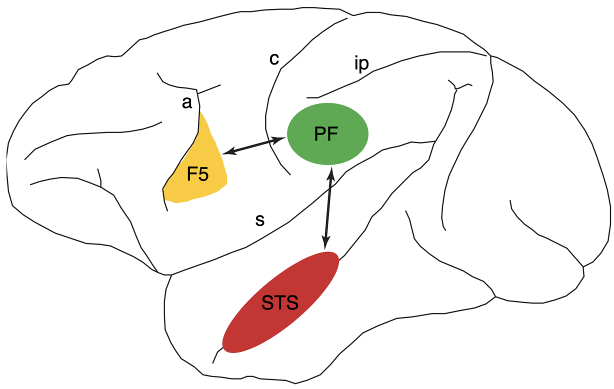


Figure 2.2: ***Lateral view of the MN circuit in the macaque brain:*** *Localisation of area F5 in ventral premotor cortex, area PF of the inferior parietal lobule and the superior temporal sulcus (STS), and their anatomical connections (arrows). Abbreviations: a, arcuate sulcus; c, central sulcus; ip, intraparietal sulcus and s, sylvian sulcus (adapted from from Keysers and Perrett (2004).*

Beside F5, the Mirror Neuron System (MNS) also includes neurons with mirror properties that are located in the rostral part of the inferior parietal lobule (or PF) (e.g., Gallese, Fadiga, Fogassi, & Rizzolatti, 2002) and is functionally related to the Superior Temporal Sulcus (STS) (Gallese & Goldman, 1998) (see Figure 2.2 for a visual representation of the monkey's mirror neuron circuit). Most of PF neurons are characterised for being responsive to sensory stimuli, but about half of them also have motor properties. PF neurons have been divided in somatosensory, visual, and bimodal (somatosensory and visual) neurons. About 40% of the visually responsive neurons are activated during action observation and 2/3 of them have mirror properties (Gallese et al., 2002). STS is also involved in motion analysis (Bruce et al., 1981; Perrett et al., 1982; Hasselmo et al., 1989; Oram & Perrett, 1994, 1996): some neurons in the anterior part of STS are selectively responsive for body movements while are not activated by static images (Jellema, Baker, Wicker, & Perrett, 2000). However, STS is not considered part of the MNS since none of the neurons in this area have motor properties (Rizzolatti & Craighero, 2004). Gallese and Goldman (1998) suggested that the "action detecting" mechanism found in STS provides an initial "pictorial" description of the action that would then feed to the F5 motor vocabulary, where it would acquire a meaning in terms of goal-directed action. To summarise, the two main cortical areas in the monkey's mirror neuron system are the ventral premotor cortex (F5) and the rostral part of the inferior parietal lobule (PF). The Superior Temporal Sulcus is functionally related to it but it is not considered a structural part of the mirror system because it lacks motor properties.

2.1.2 The human mirror neuron system

Although practical and ethical issues related with the insertion of microelectrode probes in the human brain have not allowed the gathering of direct evidence to support the existence of mirror neurons in humans (but see Mukamel, Ekstrom, Kaplan, Iacoboni, and Fried, 2010), there is an overwhelming amount of indirect data obtained in neurophysiological, neuroimaging and behavioural studies showing that a network with mirror properties following action perception and motor imagery does exist in humans.

Before discussing the structural and functional characteristics of the human mirror neuron system, it is worth making two specifications.

First, for an easier reading, I will always use ”MNS” when referring to evidence gathered from human participants. However, considering the scarcity of direct evidence, ”putative MNS” would be a more appropriate nomenclature and one that is more often found in literature. Second, I will refer to the person (or persons) not performing the action as ”observers” when talking about general properties of the human MNS. However, some experiments discussed here show that mirror activity is elicited not only when watching an action but also when listening or imagining an action.

The first evidence reporting motor activation during the observation of an action came from an electroencephalography (EEG) study by Gastaut and Bert (1954), in which mu rhythm desynchronisation was recorded during overt motor activity but also during the observation of actions performed by someone else. The mu rhythm is an index of motor relaxation and it is desynchronised during action execution: the fact that this index desynchronises when participants are completely relaxed and are watching an action performed by someone else suggests the existence of a mirror mechanism similar to that studied in monkeys. More direct evidence of the existence of a mirror system in humans comes from TMS studies. TMS is a non-invasive technique that elicits motor evoked potentials (MEPs) in contralateral muscles when applied with appropriate intensity on the motor cortex, and it is widely used to study mirror response in humans (for a review of 85 studies see Naish, Houston-Price, Bremner, and Holmes, 2014). The adoption of TMS in action observation studies is based on the principles that *i)* an overt action is always preceded by a covert stage (i.e., the representation of that action) and *ii)* the covert stage of an action is not necessary followed by an overt action (Jeannerod, 2006). That is, the representation of an action always activates the relevant neurons in the primary motor cortex (M1) but such activation remains under a certain level of threshold when the execution of that action is not required, such as during the observation of an action or in motor imagery. When applying TMS on the primary motor cortex, it is possible to make these under-threshold active neurons gain action potentials level, which ultimately allows researchers to record their overt activity at the muscular level (by means of MEPs) and to discriminate those situations in which motor representations become active in the human brain (e.g., Borroni & Baldissera, 2008). For example, Fadiga et al. (1995) recorded MEPs from participants' right hands and arms while applying TMS on the left M1. Results showed that MEPs were higher when subjects watched a reach-to-grasp action or an intransitive arm movement compared to MEPs recorded when no action was displayed (i.e., during the observation of a 3D object) (see Figure 2.3). Further, the activation selectively involved those muscles that the participant would have had to use for executing the observed movements.

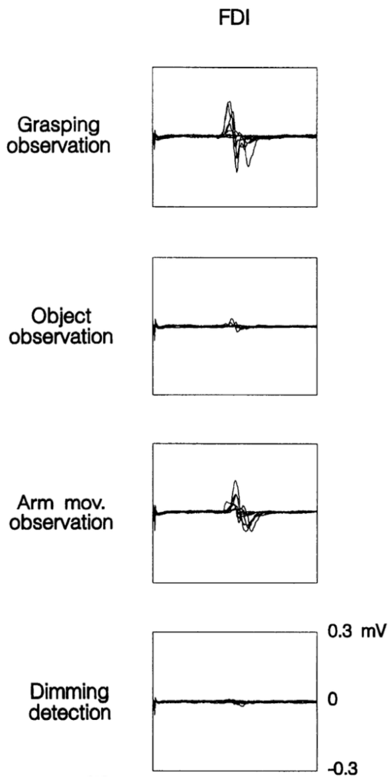


Figure 2.3: ***Fadiga, Fogassi, Pavesi, and Rizzolatti (1995): FDI activation during the observation of movements and non-movements*** *Motor Evoked Potentials recorded on the First Dorsal Interosseus (FDI; the dorsal muscle laying between the thumb and the index finger) during the observation of movements compared to control conditions. Traces are aligned with the stimulus onset. (Adapted from Fadiga, Fogassi, Pavesi, and Rizzolatti, 1995)*

While neurophysiological experiments became popular after the pioneering study by Fadiga et al. (1995), and have been necessary to support that neurons in the human motor system become active during action observation, they do not provide information on which are the brain areas involved in the human MNS. Data on this topic have been collected using brain imaging techniques, which have shown that actions performed by others activates a complex brain network of occipital, temporal, and parietal areas (e.g., Buccino et al., 2001; Grafton, Arbib, Fadiga, & Rizzolatti, 1996b; Grezes, 1998; Iacoboni et al., 1999). Although a precise localisation is still difficult (Molenberghs, Cunnington, & Mattingley, 2009) and the interpretation of brain-imaging studies in cytoarchitectonic terms is risky (Rizzolatti & Craighero, 2004), neuroimaging evidences seems to support that the ”core” neural substrates of the human MNS are homologous of the MNS found in monkeys. In particular, the human MNS relies on the activation of STS (sensitive to biological motion and responsible for sending complex visual stimuli to the rest of the mirror system; Grossman, Battelli, and Pascual-Leone, 2005), the pars opercularis of the inferior frontal gyrus (corresponding to the monkey’s area F5; Grafton et al., 1996b) and the inferior parietal lobule (IPL; Rizzolatti, Fogassi, and Gallese, 2002).

2.2 Action prediction and goal ascription

Motor representations serve different purposes. Action generation is the most obvious, but others are action prediction and imitation learning. The focus of this section is goal ascription because of the putative relevance that outcomes represented motorically have in predicting and understanding someone else’s action (Rizzolatti et al., 2001; but see Hickok, 2014 for a critical view).

Many studies report that observed actions are coded in the motor system at a low- muscle-specific level which strictly reflect how that action is carried out kinematically (e.g., Cavallo, Becchio, Sartori, Bucchioni, & Castiello, 2012; Fadiga et al., 1995). However, contextual elements that are actual or non-actual, perceived or imagined, can drastically change how a means-to-an-end action is actively planned and performed, as well as how it is coded in the motor system of a passive observer. In fact, actions that are directed towards a goal are planning-like in the sense that they involve computing the best way of doing something now (based on the context) to achieve something later (i.e., to achieve the goal) (e.g., Jeannerod, 2006). As an example, when you reach-to-grasp a baseball, there is a set of typical movements that you are required to plan and execute in order to successfully achieve your goal of getting the baseball. In simple terms, we can consider this necessary set of bodily movements and their means-to-ends relations as granted (e.g., Butterfill & Apperly, 2016), and they might include arm extension, hand opening and hand closure. However, the context defines the best way for you to organise your movements now in light of the fact that you want to grasp the ball later. For instance, in broad daylight, the best way might be to fixate on the incoming target and to perform a fast and sharp set of bodily displacements when the ball is getting close. Late at night and in poor visibility, you might want to start by cautiously raising your arm and open your hand early to avoid the ball hitting you in the face.

Indeed, it has been shown that performing a reach-to-grasp action is influenced by contextual elements such as the size (e.g., Ansuini et al., 2015; Bootsma, Marteniuk, MacKenzie, & Zaal, 1994), location (e.g., Kudoh, Hattori, Numata, & Maruyama, 1997; Paulignan, Frak, Toni, & Jeannerod, 1997) or familiarity (e.g., Gentilucci, 2002) of an object. And the planning of an action is a multisensory process. When you ask participants to grasp a visually presented object with one hand, their kinematics (e.g., maximum hand aperture) will be impacted if there is a competing motor representation, for example triggered by holding a different-sized object with the other hand (e.g., Gentilucci, Daprati, & Gangitano, 1998; Patchay, Haggard, & Castiello, 2006), or by hearing a sound that is incongruent with the sound of the contact target (e.g., aluminium-sound when reaching for a paper object; Castiello, Giordano, Begliomini, Ansuini, and Grassi, 2010; Zahariev and MacKenzie, 2007) or even by smelling a fruit that has a different size of the one they are reaching for (e.g., smelling a strawberry when reaching for an apple; Castiello, Zucco, Parma, Ansuini, and Tirindelli, 2006) (for a review of the multisensory aspects associated with action execution see Betti, Castiello, and Begliomini, 2021).

Action planning and execution is not only supported by the information that is present in the actual multisensorial context, but is also sensitive to non-actual environments such as the ones that are generated when engaging in motor imagery-based mental practice. In fact, although motor imagery is the internal rehearsal of movement without any overt movement (Jeannerod, 1994), it has been shown to have real-life effects in both supporting the rehabilitation of patients suffering motor dysfunctions (e.g., Li, Du, Yang, Wang, & Wang, 2022; Monteiro et al., 2021) and enhancing performance in athletes (Dello Iacono, Ashcroft, & Zubac, 2021; Guillot, Rienzo, Frank, Debarnot, & MacIntyre, 2021). It is indeed well established (Mellet, Petit, Mazoyer, Denis, & Tzourio, 1998) that during motor imagery there is a similar neural activation that occur when preparing (Jeannerod, 1994) and executing (Lotze et al., 1999; Porro et al., 1996) an action (for a review of techniques used to evaluate motor imagery, see Guillot & Collet, 2005). For example, studies using Positron Emission Tomography (PET) show that when participants are asked to imagine to grasp a visually presented object (Decety et al., 1994; Grafton, Arbib, Fadiga, & Rizzolatti, 1996a; Grèzes & Decety, 2002) or to move a mentally represented joystick (Stephan et al., 1995) there is an increase in regional Cerebral Blood Fluid (rCBF) in those same cortical and subcortical regions that are involved in action execution.

At the same time, and importantly for us, several studies also show that also during action observation the action is not only coded in terms of pure kinematic features but also on the basis of the goals and the best way to achieve them, as observed at both the neural (e.g., Cattaneo, Sandrini, & Schwarzbach, 2010; Rizzolatti & Sinigaglia, 2010) and behavioural level (e.g., Ambrosini, Costantini, & Sinigaglia, 2011; Zwaan et al., 2012). An example comes from the work of Ambrosini et al. (2011). In their experiment, the authors measured anticipatory eye movements to investigate whether participants could use the early kinematic information provided by a moving hand to predict the goal of such motion. Here, participants watched videos in which an agent reached for and grasped either a small object with a precision grip (PG) or a large object with whole-hand grasp (WHG). Results showed that participants were fast and accurate in looking at the target that was actually the target of the action before the movement was complete. That is, when the agent pre-shaped a PG, participants looked in anticipation towards the small object and, when the agent pre-shaped a WHG, they looked towards the large object. This evidence is suggestive for the existence of a rapid and implicit motor mechanism in the observer that allow goal ascription. Further, this also generates the testable prediction that, if the ability of the observer to use his own motor system is impaired, for example by temporally constraining him (Ambrosini, Sinigaglia, & Costantini, 2012) or by disrupting his motor-related cortical activation (Brich, Bächle, Hermsdörfer, & Stadler, 2018; Costantini, Ambrosini, Cardellicchio, & Sinigaglia, 2014), his ability to motorically represent the goals of others' actions will be impaired. In line with this, Costantini et al. (2014) used similar video stimuli to those adopted in the experiment by Ambrosini et al. (2011) to show that participants are unable to use the information provided by the pre-shaping configuration of a moving hand to proactively gaze towards the actual target of that action when their hands are tied behind their back. Participants' action prediction is impaired not only when they are unable to perform the observed actions themselves; participants' action performance is also impaired when they have to actively perform an action while watching a (irrelevant to the task) constrained agent. For instance, Liepelt et al. (2009) instructed participants to lift their index or middle finger in response to a number stimulus presented between the index and middle finger of a photograph of an agent's static hand. Participants' reaction times were slower when the agent's index and middle fingers were tied compared to when the agent's fingers were not constrained and compared to when the agent's constrain involved fingers not involved in the participant's action (thumb and ring finger).

In addition, there are also studies showing that the link between action observation and action execution is not just a matter of motorically simulating the specific muscles or kinematics and that adults can automatically ascribe the goal an action is directed towards regardless of the specific effector used (Betti, Castiello, & Sartori, 2015; Rizzolatti & Sinigaglia, 2010) or the perceptual availability of the movements (Jeannerod, 2006). For example, adults observing someone wearing a miniaturised soccer shoe kicking a ball with the index finger show motor facilitation in their own index finger but also in their leg (Betti et al., 2015). Betti and colleagues used TMS to record MEPs in the hand and leg muscles of participants who were watching a symbolic action that is classically performed with the leg (i.e., a football kick) being carried out with the index finger by an agent. The results showed motor activation in the specific muscle involved in the observed action (i.e., the hand: first dorsal interosseus) but crucially also in the effector that is typically engaged when performing that symbolic action (i.e., the leg: quadriceps femoris). On the contrary, only the hand muscle becomes active during the observation of a biological motion that is the same to the one employed when kicking the ball with a finger in terms of joint displacements but without a symbolic value to it (i.e., when the finger does not wear a miniaturised soccer shoe). In other words, while the observer's motor system resonate with the low-level movements involved in the observed action (Cavallo et al., 2012; Fadiga et al., 1995), it also codes for the goal of an action, regardless of how things actually are in the environment (Butterfill & Apperly, 2016; Cattaneo, Caruana, Jezzini, & Rizzolatti, 2009).

Further, behavioural studies also show that, similar to how the human motor system codes for the best way to achieve the goal of an action regardless of the observed kinematics, as we saw in the ”kick with the finger” experiment, the motor system takes into consideration the most efficient way of achieving the goal during motor imagery as well, regardless of how things actually are (that is, regardless of the fact that in reality the thinker is not actually performing any movement). For example, Decety, Jeannerod, and Prablanc (1989), as well as Decety and Lindgren (1991), compared the duration of purely mentally performed actions and actually performed actions. Their results showed that, when participants were executing a walking action towards a target, they took a similar amount of time compared to when they were imagining that same action. And the time taken to both perform and think about an action increases as a function of real or imagined movement constraints: participants took more time to walk but also to think about walking, on a narrower beam compared to a larger beam. More recently, it has been shown that motor imagery invoked by linguistic stimuli influences motor plans and automatic postural leaning (Zwaan et al., 2012). The authors found that when participants stood on a Wii balance board with the instruction to read sentences implying a forward- leaning posture (e.g. ‘He dove into the pool’) or a backward-leaning one (e.g. ‘The teenager plopped down on the couch’), readers’ own postural sway was congruently influenced by the implied action.

In the multisensory complexity of the world , it is essential to predict the likely behaviour of other agents for understanding (e.g., Rizzolatti et al., 2001) what they do and for eventually planning our own behaviour (e.g., Sinigaglia & Butterfill, 2022). The fact that a passive observer generates motor representations of goals that are relatively distal from the observed bodily configurations and joint displacements, as I have discussed above, facilitates such predictions. Multiple experiments specifically designed to investigate action prediction have shown that an observer can anticipate the outcome of an action when the outcome is unpredictable (e.g., when the context alone allows for multiple possible outcomes). Indeed, it has been shown that by correctly reading the movement kinematics it is possible to identify the success or failure of a basketball shot (Aglioti, Cesari, Romani, & Urgesi, 2008), the direction of a tennis ball (Shangguan & Che, 2018) or which target a moving hand is reaching for (e.g., Ambrosini et al., 2011).

To conclude, it has been extensively reported that goal ascription occurs when one own's motor system simulates the motoric means required to achieve the outcome to which an observed (or imagined) action is directed. That is, not only when executing but also when observing or imagining an action our motor system generates predictions based on what we know is the best way to carry out the goal of that action.

2.2.1 Theoretical challenges

Since their discovery, mirror neurons have sparked significant scientific interest. They have been implicated in all sort of fields such as autism, schizophrenia, language comprehension, empathy and post traumatic stress disorder. Their favourable and catchy name has also helped in attracting the attention of the general public, which in turn has called for the use of even more bold metaphors of the like of ”the neurons that shaped civilisation” (Ramachandran, 2009). Most of the far-reaching claims associated with the role of the mirror neurons have been, to say the least, tempered down during the course of the years. However, arguing whether some of these claims were or were not scientifically sound to begin with it is not relevant for my thesis (but for a review on this topic, see Heyes and Catmur, 2022).

The theoretical challenge discussed here concerns what it is that the motor output codes for during action observation. In the previous section, in my attempt to stay on topic and outline some of the existing empirical evidence that points in the direction of motor processes that code for the goals of an observed or imagined action, I have in fact neglected competing accounts on action observation.

There is little doubt that actions performed by others activate mirror neurons in the observer, and even the most skeptical of authors agree on this (e.g., Gallese et al., 2011; Heyes, 2010; Hickok, 2009, 2014). Nevertheless, what actually is coded by the motor system during action observation is a debated topic. Actions can be describe at different hierarchical levels. Actions have (1) an intention level that defines the long-term goal of an action, (2) a goal level that describes the short-term goals, (3) a kinematic level that describes the spatial and temporal features of the movement, (4) a muscle level that describes the pattern of muscle activity required to execute that action (Grafton & Hamilton, 2007; Kilner, Friston, & Frith, 2007). To understand (and anticipate) an observed action, the observer has to code the action not only in terms of the muscles and kinematic involved but also on the base of its goals (e.g., Kilner et al., 2007; Sinigaglia & Butterfill, 2016), and some of the evidence seems to point in this direction. But how can it?

Since their name was coined, mirror neurons have been suggested to be cells that encode goals to allow the observer to directly understand the actions of others (di Pellegrino et al., 1992; Rizzolatti, Fadiga, Gallese, & Fogassi, 1996) "from the inside" (Rizzolatti & Sinigaglia, 2010) and without the need of effortful inferential processing (e.g., Rizzolatti & Sinigaglia, 2008). According to the direct-matching hypothesis (Rizzolatti et al., 2001), an observer's motor system resonates with an agent's motor system, and the motor representation stored in the observer is used to understand (by matching) the observed action. The idea here is that visual information is transformed into knowledge (Rizzolatti & Craighero, 2004; Rizzolatti et al., 2001) and the assumption is that such information is passed by forward connections in the MNs network and transformed from the low-level representations of the muscles and movement kinematics involved to higher-level representations of goals. According to this account, action understanding is achieved through the sequential activation of the Superior Temporal Sulcus (STS; provides visual description of the action), which activates parietal mirror neurons in the Inferior Parietal Lobule (IPL; concerned with motoric aspects of the action), which in turn activates frontal mirror neurons in the Inferior Frontal Gyrus (IFG; provides the goal of the action) (e.g., Iacoboni & Dapretto, 2006) (see Figure 2.4).

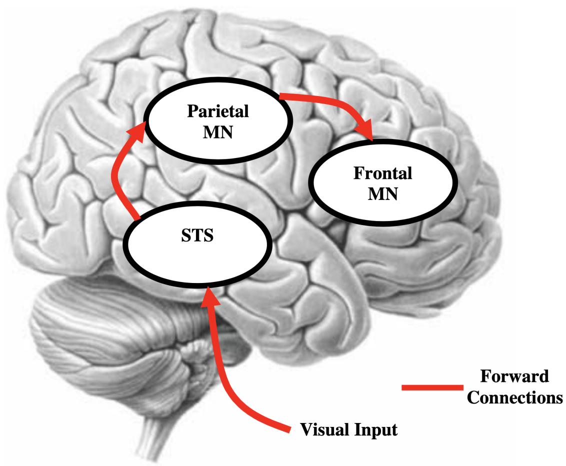


Figure 2.4: ***Forward model for action recognition***: *forward model of how motor activation in the observer can capture goals to which actions are directed (adapted from Kilner, Friston, and Frith (2007).*

Further, the execution and understanding of new meaningful actions would be facilitated by the anatomical connections between these MNS areas, which are strengthen and renewed according to Hebbian rules of learning (Keysers & Perrett, 2004), according to which ”neurons that fire together, wire together” (Hebb, 1949).

One of the problems with the forward model is that, during action observation, the forward-directed cascade of events initiated by the observed motor commands can lead to the identification of only one possible goal of the action (Kilner et al., 2007). However, as I have already discussed in the previous chapter, the same motor input can be directed to different goals. For example, a person sitting at the bar can initiate a series of movements to reach to grasp his phone or reach to grasp his beer.

One possibility is that contextual information would trigger the parallel activation of different forward models that are compatible with the observed action, all of which are viable candidates to make predictions about the sensory consequences of that action (Wolpert & Flanagan, 2001). Modulation of the observers' motor system would occur when the observed and the predicted kinematics made by one of the models matches the sensorimotor features of the observed action. On the contrary, a mismatch between predicted and the observed kinematics would not lead to motor activation in the observer.

Alternatively, Kilner et al. (2007) propose that the MNS employs a predictive coding of the information at all levels to ensure that the error in goal and intention ascription is minimised. In this scheme, each hierarchical level of the action is connected by forward but also backward connections, allowing for online updates based on how the action evolves. For example, if an agent believes his wedding ring to be stored in a right box instead of a left box, an observer can predict that the goal of the agent is to reach the right box. Given the goal, he can predict the motor commands. Given the motor commands he can predict the kinematics. Using his motor system, the observer can compare the predicted kinematics with the observed kinematics to generate a prediction error and eventually update the motor representations of the agent's motor commands and goals. Similarly, in what they call functional goal tracking, Sinigaglia and Butterfill (2016) also support the idea that a mismatch between the predictions generated at the behavioural level and the observed behaviour is what ensure that often enough the incorrect representations of outcomes are weakened and that the motor representation of the actual goals are retained (see Figure 2.5).

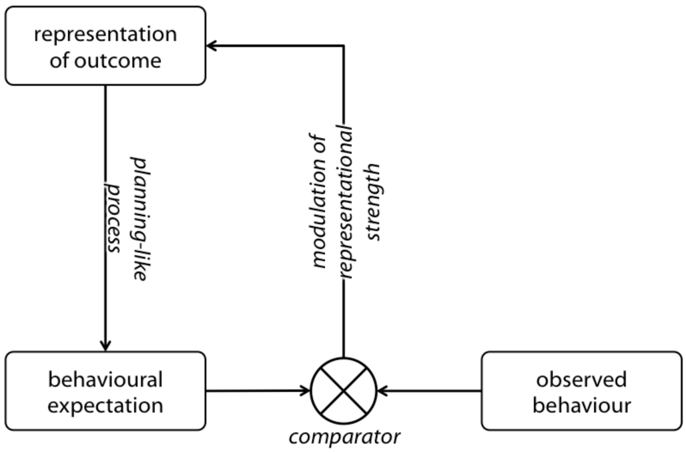


Figure 2.5: ***Sinigaglia and Butterfill (2016)****: model of how motor processes in the observer can capture goals to which actions are directed.*

However, the view that motor activations in the observer can serve the function of goal ascription and action understanding has not gone unchallenged. For example, (Csibra, 2007) argues that cognitive, inference-based, predictions about the goals of an action are generated outside the motor system and that mirror neurons are activated only after top-down goal ascription. In his *emulative action reconstruction* hypothesis Csibra outlines that the low-level characteristics of an action such as its kinematics are reconstructed at a MNS level on the basis of a priori assumptions or interpretations of the goals. That is, from the author's point of view "it is not action simulation that makes action understanding possible but the other way around".

Similarly, Saxe (2005) interprets the performance of children and adults in tasks designed to focus on mental representations underpinning observers' reasoning about another person's behaviour (e.g., Kruger & Gilovich, 1999; Ruffman, 1996) as evidence that, when explicitly asked to predict or explain an action or inference, they do not use motor simulation but instead deploy an intuitive theory of how the mind works. From Saxe's perspective, the fact that observers make judgment mistakes that are congruent with their beliefs about how minds work suggests that they are generating explanations by using their beliefs as a reference.

Further, in her associative learning account, Heyes question the functionality of the mirror neurons on the basis of their origins (Gallese et al., 2011; Heyes, 2001; Heyes, 2010). According to Heyes, one should accept the idea that action understanding is primarily achieved through MNS activity only if mirror neurons were the result of adaptation, or natural selection, which favoured them specifically for the function of understanding actions. On the contrary, Heyes advocates that association through sensorimotor learning plays a ”forging” role in the emergence of motor neurons with mirror properties. That is, mirror neurons are only a byproduct of adaptation. In her view, as much as we have white bones because natural selection favoured calcium, we also have mirror neurons because by adaptation ”neurons that fire together, wire together”. However, Heyes concedes that although mirror neurons may not evolve for action understanding or any other function, it is possible that mirror neurons are recruited to make a contribution to action understanding.

To conclude, accounts arguing in favour of motor representation coding for the goals of an action have sometimes implicitly suggested (e.g., Rizzolatti & Craighero, 2004) that the motor way is the mandatory way. On the opposite side of the spectrum, other authors have contended that understanding an action is a top-down inferential process and that the role of the motor system is, at best, to provide some kinematic description of the action (e.g., Saxe, 2005). While the former approach emphasises the pre-reflective and perhaps automatic (e.g., Iacoboni et al., 1999; Rizzolatti et al., 2001) role played by the motor system, the latter emphasises that human beings have a social–cognitive system that guides the anticipation of others' action in a top-down fashion. Besides the ground being contested by radical views, here I suggest, in line with the conjecture proposed by Butterfill and Apperly (2016), that exploitation of planning-like motor processes elicited during action observation ensures that, often enough, outcomes represented motorically in the observer of an action are actually goals of the observed action. In this way, some (but not all) forms of goal ascription can be achieved in a cognitively efficient way whereby the only representations are motor representations. This consideration is supported by extensive evidence, some of which I provided in section 2.2. However, this does not preclude the coexistence of higher level processes that are the primary responsible for other kinds of goal ascription, which could be achieved with the support of a motor facilitation (Sinigaglia & Butterfill, 2016) or without any motor representation at all (e.g,. Hickok, 2009) such as in cases where unfamiliar actions selectively activate brain areas associated with flexible mindreading (Brass, Schmitt, Spengler, & Gergely, 2007) while inhibiting motor resonance (e.g., Amoruso, Finisguerra, & Urgesi, 2016).

Chapter 3

The Current Research

I concluded the previous chapter by arguing that sometimes motor representations of an observed action are the only representations required to achieve goal ascription. As we have seen, this has been a classic topic for discussion in the motor cognition field, and in more recent years it has gained relevance for the mindreading arena as well. Proponents of the 2-systems of theory of mind suggest that motor processes and representations might be cognitively efficient in the way required for automatic, minimal mindreading. However, whether and how motor and minimal mindreading processes might be functionally connected is still unclear.

The different theoretical approaches have studied action observation and understanding from distinct perspectives. As discussed in Chapter 1, the mindreading approach emphasizes that human beings have a social-cognitive system that guides rapid anticipations of others' belief-based action (Apperly & Butterfill, 2009; Edwards & Low, 2017), and this fast mindreading system may operate even when the tracking of belief-relevant information is immaterial to the task at hand (Grainger, Henry, Naughtin, Comino, & Dux, 2018; Nijhof, Brass, Bardi, & Wiersema, 2016; van der Wel et al., 2014). The motor cognition approach emphasizes the pre-reflective role played by human beings' motor system in the understanding of others' actions. Here, as discussed in Chapter 2, the idea has been that action observation elicits motor representations and processes in the brain of the observer, which are similar to those occurring during action execution (Rizzolatti et al., 1988; Rizzolatti & Sinigaglia, 2010). Mindreading and motor approaches to action observation and understanding are often considered separately. Even though meta-analysis work indicate that they rely on distinct brain networks (e.g., Van Overwalle & Baetens, 2009), and although such networks are anti-correlated during rest (such as when participants look at a fixation cross; Uddin, Clare Kelly, Biswal, Xavier Castellanos, and Milham, 2008), their independence could be the result of experimental paradigms designed to isolate one process or the other rather than functional differences (Gobbini, Koralek, Bryan, Montgomery, & Haxby, 2007; Grafton, 2009; Keysers & Gazzola, 2007; Spunt & Lieberman, 2012). In the mindreading field, experimental tasks are designed to focus on mental representations underpinning observers' tracking or reasoning about another person's mistaken belief-based behaviour (Low & Perner, 2012). While informative, such tasks tend to neglect potential activations in participants' own motor system that can be revelatory of observers' rapid online action understanding. The focus of research in the motor arena, by contrast, has been on situations where the observed action convey little social content to emphasise bodily kinematics (Becchio et al., 2012). Then, it is reasonable to suggest that in tasks whereby actions directed to a goal are performed in context-relevant scenarios there may be increased activity in both the mindreading and the mirror neurons system. For instance, co-activation is found when the observed action is performed socially as opposed to individually (Begliomini et al., 2017; Centelles, Assaiante, Nazarian, Anton, & Schmitz, 2011), or when the observer is processing higher levels of intention (such as why the agent is doing what is doing) (Chambon et al., 2017).

A further case in point is that only the motor system becomes active in the observer during the mere observation of a goal-oriented action but both the mindreading and the motor network become active if the observer is prompted to reasons about the agent's mental state (Thioux, Suttrup, & Keysers, 2018). Thioux and colleagues captured fMRI images of participants watching same-length videos of an agent reaching a big ball or a small ball with either a confident or a hesitant motion. The authors speculate that hesitation is a mental state that is not too abstract to be completely detached from the kinematics. Consequently, they manipulated hesitation in goal-oriented action to have a task that had enough social content without losing the emphasis on bodily kinematics. Before each block of videos, participants were requested to make a guess about the upcoming 6 videos. In the Target condition, they were asked to estimate how many times the actor was going to grasp the big ball. In the Hesitation condition, they were asked how many times the actor was going to be unsure about which ball to choose. Their results show that only the mirror system becomes active in the Target condition. On the contrary, when participants are motivated in thinking about the agent's mental states (that is, in the Hesitation condition), both the mirror system and the mindreading system become active. Further, since disrupting neural activation in the observer's motor areas (by means of repetitive Transcranial Stimulation; rTMS) has been shown to negatively impact the ability to predict goal directed actions (Costantini et al., 2014), Thioux and colleagues show that disturbing the motor network also results in impaired action-hesitation attribution (cue to mindreading processes). In a variation of their Hesitation task, Thioux et al. had participants performing a reaction time task following rTMS on motor or mindreading brain areas. In the Target condition, after watching the video, participants had to press a right or left foot pedal to indicate that the agent was reaching for the big ball or not. In the Hesitation condition, they had to press one of the pedals to indicate whether the agent was hesitant or not. Their findings show that, in the Target condition, using rTMS to temporally impair motor areas produces slower reaction times, but rTMS over mindreading areas has no effect in slowing down participants' attribution of the goal of an observed action. On the contrary, in the Hesitation condition, not only rTMS over mindreading areas but also rTMS over motor areas produces slower reaction times, suggesting that both networks are necessary to optimally attribute mental states (e.g., hesitation) to an agent who is performing a goal-oriented action. Thus, there is some initial evidence that when observing another person's actions while reasoning about his mental states both motor and mindreading processes become active, and that impairing the motor representations in the observer might result in the disruption of mindreading abilities. However, minimal mindreading as proposed by the 2-systems of theory of mind does not involve reasoning about the same kinds of states that are involved in tasks implemented in the study of non-automatic mindreading. In fact, minimal mindreading does not involve reasoning about beliefs as such. In contrast with the flexible system, the minimal system is automatic and represents belief-like states (i.e., registrations). The existence of a functional relationship between motor and minimal mindreading is a recent concept (Butterfill & Apperly, 2016; Low, Edwards, & Butterfill, 2020; Sinigaglia & Butterfill, 2016; Sinigaglia, Quarona, Riva, & Butterfill, 2021) and, as of today, the processes that might be involved are still poorly understood.

3.1 Minimal Mindreading and Motor Processes

Chapter 1 alluded to the challenge that the motor system faces when complex social situations require the tracking of an agent's false belief to successfully identify the outcome to which an action is directed. As a reminder, imagine that Sofia performs an action the goal of which is to retrieve a bar of chocolate. She falsely believes that the chocolate is inside the yellow box, whereas actually it is inside the pink box. If we (that is, our motor system) fixate on her goal of retrieving the chocolate, we will generate the wrong prediction that she will reach for the box containing the chocolate. On the contrary, we need to track Sofia's belief to correctly identify the motor outcome of her action, which is that she will reach for the empty box. Since motor processes generate action predictions not only when perceiving an action through our senses (e.g., Betti et al., 2021) but also when we imagine to perform an action (e.g., Decety & Lindgren, 1991; Jeannerod, 2006; Lotze et al., 1999), it is at least coherent to conjecture that, when observing an agent, planning-like motor processes are not bound the the actual state of reality but are also modulated by how the reality is registered by the agent (which might differ, such as in the case of false beliefs, form how the state of reality actually is). That is, it might be that an observer's motor system generates expectations of the best way to do something now, in light of something that will be achieved later, by taking into account not only facts about the actual environment but also facts about the environment as specified by the agent's registrations. Initial evidence indicating that an agent's registration (for example about the location of an object) is the kind of information that an observer can pick up quickly and in a cognitively efficient way comes from studies showing that processing registrations is subject to signature limits (Edwards & Low, 2017; Fizke et al., 2017; Low et al., 2014; Low & Watts, 2013), which mark a line (so to speak) after which mindreading requires explicit and cognitively effortful reasoning. Motor processes have been identified as the likely mechanism capable of integrating and make use of such low-level registrations during action observation. In fact, motor processes and representations generate fast and planning-like action prediction in the cognitively efficient way required for minimal mindreading (Butterfill & Apperly, 2016).

How could planning-like motor processes in the observer generate action prediction by taking into account not only facts about the actual environment but also facts about the environment as specified by the agent's registrations?

As we have seen in Chapter 2, outcomes such as reaching to grasp a ball can be represented motorically and motor representations of outcomes can generate expectations or predictions concerning another agent's behaviour. Following the model outlined by Butterfill (2019), these predictions are compared with the actual observed behaviour (cfr. *(a)* in Figure 3.1) and the result of this comparison modulates the strength (cfr. *(b)* in Figure 3.1) of the motor representation of the outcome (cfr. *(c)* in Figure 3.1). This modulation will ensure that, often enough, an outcome represented motorically is likely to be a goal of the observed action (Kilner et al., 2007; Sinigaglia & Butterfill, 2016). Then, if the observer's motor system is not impaired (for instance by body constraints or neural disruption), nor tricked (such as in the case of a player performing a body feint directed to an opponent in competitive sport activity), the best motor way to achieve the goal will be coded (cfr. *(d)* in Figure 3.1) and the correct behaviour will be predicted (cfr. *(e)* in Figure 3.1).

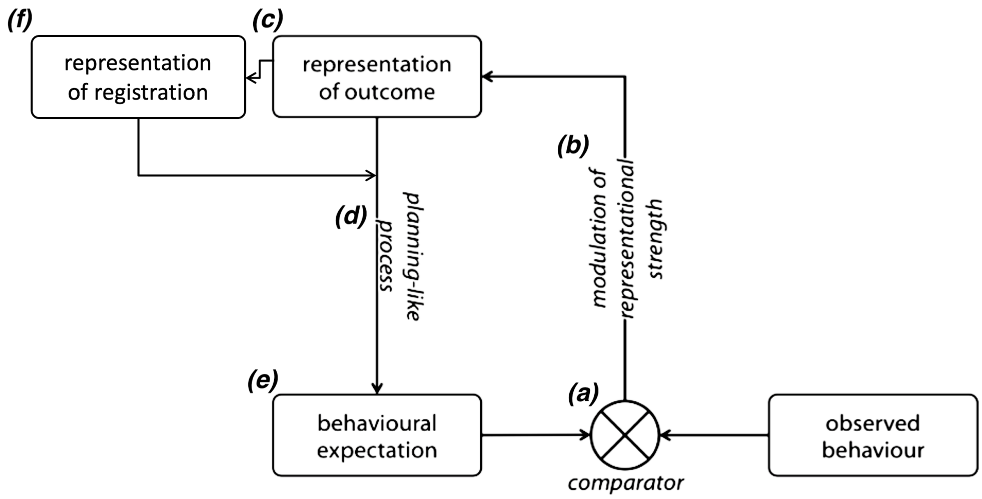


Figure 3.1: ***Butterfill (2019): motor and belief-tracking integration during action observation.*** *Model of how belief tracking (f) can influence motor processes during action observation.*

This model, as outlined so far, illustrates action prediction when belief tracking is not required. To explain the last part of the model (that is, ”representation of registration”; cfr. *(f)* in Figure 3.1) and to understand where belief-tracking comes in play, it is best to start by mentioning that, while context plays a key role in coding high-level components of others' actions, at a lower level, planning-like motor processes in the observer are also informed by the environment. The reader could think at the various aspects of the reality in which the observed action takes place as listed below box *(f)* in the figure. Similar to box (f), such contextual information would feed into and modulate the best way to do something now based on the outcome that will be achieved later. For instance, cortical activity is refined when the same observed action is performed socially as opposed to individually (Bucchioni, Cavallo, Ippolito, Marton, & Castiello, 2013) and suppressed when there is a mismatch between observed bodily displacements and the contextual possibility to act (Amoruso et al., 2016; Amoruso & Urgesi, 2016). The fact that motor processes occur in motor imagery (e.g., Jeannerod, 2006), and that when thinking about an action our motor system is sensible to the constraints of the imagined context (Decety & Lindgren, 1991; Zwaan et al., 2012), suggests that planning-like motor processes during action observation generate behavioural predictions not only based on the actual environment but also on non-actual environments, such as the ones specified by the agent's belief-like state (Butterfill & Apperly, 2016). In this way, tracking an agent's registration (for example, about the location of an object) might assume critical contextual relevance for the observer's motor system because fixating on the goal of an agent who wants to retrieve an object might lead to the wrong behavioural expectations. For instance, if the agent has last registered the location of the object where it is not anymore, the observer's motor system needs to process the information provided by representation of the agent's (incompatible with the current reality) registration about the location of the object (cfr. *(f)* in Figure 3.1) to code for the fact that the best way (from the agent's point of view) to do something now is actually to go to the wrong location. Only then, an observer can motorically represent how the agent's action is likely to unfold. That is, that the agent will initiate a series of bodily displacements aimed towards the location where she falsely believes the object is located. There is some initial plausibility to the conjecture: van der Wel et al. (van der Wel et al., 2014) found that information about someone else's belief systematically perturbed the motor processes underpinning the trajectory of adults' own hand movements on a computer mouse-tracking task.

Further, what would happen to fast-belief tracking abilities if the ability to process planning-like information is impaired? For the sake of the argument, suppose we paint a red cross over *(d)* in the model we discussed (see Figure 3.2).

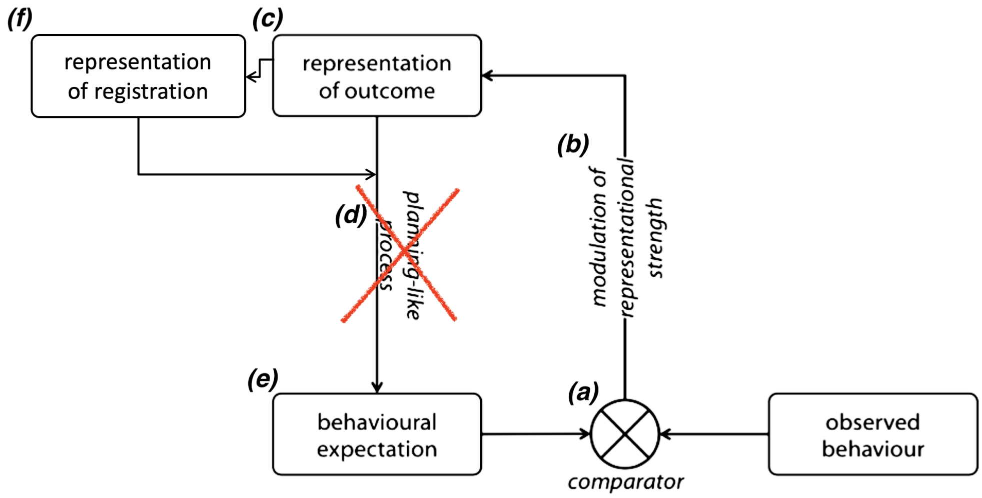


Figure 3.2: ***Effects of motor impairment on the ability to generate behavioural expectations:*** *temporally impairing the observer's ability to process the best way (d) to achieve an outcome (c) based on how the environment actually is and based on how the environment has been registered by the agent (f) also disrupts his ability to predict how the action is going to unfold (e) (adapted from Butterfill (2019)).*

What happens in this scenario since the representation of a goal (box *(c)*) is deprived from the possibility of passing the "how to" information that is necessary to anticipate the way the action will actually unfold (box *(e)*)? Without the possibility to represent how the outcome of an action can be motorically performed, action prediction, or behavioural expectation, will be impaired. This prediction has already been tested. As I have discussed in Chapter 2, by bodily constraining the agent (Liepelt et al., 2009) or the observer (Ambrosini et al., 2012), or by disrupting the onlooker's motor-related cortical activation (Brich et al., 2018; Costantini et al., 2014), the ability to generate action prediction is impaired. Accordingly, if Butterfill and colleagues are correct (Butterfill, 2019; Butterfill & Apperly, 2016; Sinigaglia & Butterfill, 2016), and the onlooker's motor system is not tied to the actual environment but also functionally incorporates the tracking of the agent's beliefs, temporally impairing motor processes in the observer would not allow to process an agent's registrations in a cognitively efficient way, ultimately disrupting the expectation of how belief-based actions unfold. Alternatively, it may be that the belief-tracking process results in a second, independent behavioural expectation, or that belief-tracking guides subjects in spontaneously predicting the agent's belief-based actions non-motorically, and these predictions then trigger motor activity. On the alternative view, belief-tracking and motor processes would not be integrated in the way that the model above outlines.

Initial support to the view that motor processes and belief-tracking are tightly integrated comes from an adaptation of the ball detection task (Kovacs et al., 2010) by Low et al. (2020). Typically, in the ball detection task, participants (P) watch a series of events resulting in them and the agent (A) believing a moving ball to be ultimately located behind an occluder or not. At the end of the sequence, the occluder is dropped and participants have to press a button as quickly as possible when the ball is present. If the agent never leaves the room during the course of the change-of-location events, participant and agent end up having the same belief about the presence (P+; A+) or absence (P-; A-) of the ball. On the contrary, if the agent left the room before the last swap in location, participant and agent have contrasting beliefs. In this case, after the agent reenters the room and the occluder is dropped, the presence of the ball can be surprising only for the participant (P-, A+) or only for the agent (P+, A-). The classic findings in this implicit (i.e., the agent's beliefs are never explicitly mentioned) task show that participants are faster to detect the ball when they and the agent believe that the ball is behind the occluder compared to the baseline condition (P+A+ < P-A-), but also that they automatically compute the agent's beliefs, as revealed by their reaction times being faster when only the agent believes that the the ball is behind the occluder compared to the baseline condition (P-A+ < P-A-). Low et al. (2020) replicate this classic effect by Kovacs et al. with adult participants. However, and crucially for us, they also show that disrupting adults' motor processes (by manipulating the agent's bodily constraints) also impairs their ability to spontaneously encode the agent's registrations about the presence of the ball. In their task, adults' reaction times reflected the agent's beliefs when the agent was free to act on the ball (i.e., they replicated the classic effect; P-A+ < P-A-) and when he reentered the scene wearing visually novel but not obstructive sheets (P-A+ < P-A-), but not when the sheets visibly constrained the agent from potentially acting upon the target (P-A+ = P-A-) (see Figure 3.3).

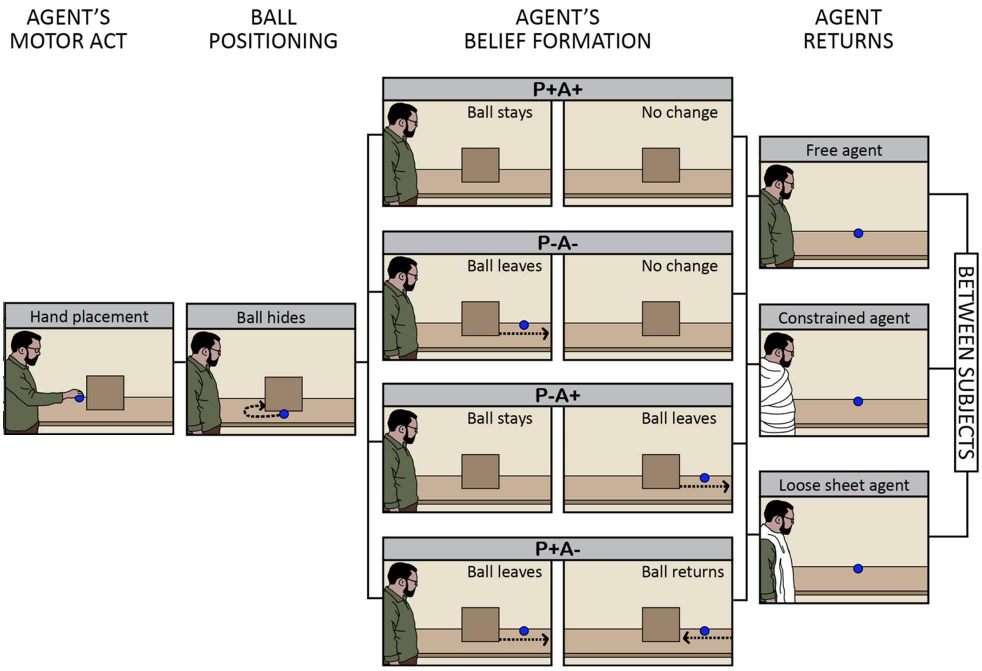


Figure 3.3: ***Low, Edwards, and Butterfill* (2020):** *visual representation of the conditions adopted by Low and colleagues in their ball-detection task. At the end of each sequence, participants had to detect the presence of the ball while experiencing a Free-Agent (no sheet), a Constrained-Agent (sheet impairing bodily displacements) or a Loose-Sheet-Agent (sheet allowing movements) coming back into the scene.*

Another study investigating the functional relationship between motor processes and minimal mindreading comes from Sinigaglia et al. (2021, Experiment 3). In the same vein as Low et al. (2020), Sinigaglia and colleagues adapted the Kovacs' ball detection task to test the idea that temporally interfering with adults' possibility to generate motor expectation of an action disrupts their ability to track an agent's registration about the location of an object. Here, participants watched a series of events that were the same as in the standard ball detection task. However, while Low and colleagues manipulated the agent's constraints (using bandages) only in the outcome phase (that is, after the occluder was dropped and the presence of the ball was revealed), here the agent was encased in a box made of trasparent plexiglass, which prevented the interaction with the ball before, during and after the belief acquisition phase. Their results confirmed and extended the Low et al.'s findings in that participants' reaction times to the presence of the ball was not influenced by the beliefs of an agent who was unable to act (P-A+ = P-A-). Taken together, the initial evidence provided by Low et al. (2020) and Sinigaglia et al. (2021) supports the conjecture that motor processes and belief-tracking are tightly linked and that disrupting adults' motor processing also impairs their ability to spontaneously encode the agent's registrations about the location of an object in a ball detection task. Although more research needs to be done to disentangle the timing of this effect, the fact that the belief-tracking inhibition is not only obtained when the constraint manipulation occurs early in sequence of events (i.e., Sinigaglia et al., 2021), but also at the moment in time when participants need to process the scene as quickly as possible (i.e., Low et al., 2020) lends support to the conjecture that minimal mindreading might need to leverage a cognitively efficient process of the like of the one provided by the motor system.

Without taking away the important insights coming from the work done in Low and Sinigaglia's labs, the initial evidence they both provide comes from participants' reaction times measured in ball detection tasks whereby the agent has limited to none interaction with the target object. In particular, while in Low et al. there is some kinematics involved (i.e., at the beginning of the sequence of events, the agent performs himself the action of placing the object on the scene), in Sinigaglia et al. the agent never moves. However, as we have seen, the separation between the mindreading and the motor cognition field is associated with their experimental tradition marked by paradigms respectively used to artificially isolate one process: perceived kinematics with reduced contextual information for testing the motor representations and processes; observers' tracking or reasoning about another person's mistaken belief-based behaviour to study mindreading abilities. Consequently, a step forward in the direction of better understanding the functional relationship between motor and mindreading processes might involve having a task in which it is possible to preserve both the perceived motor behaviour and the social content. For this reason, I started my experimental work by adapting the Buttleman's real-time interactive helping task (2009). In fact, although it was originally designed to study spontaneous belief reasoning in infants, this task is a good candidate to study whether adults' motor representations play a deep role in tracking others' beliefs because it involves real-life agents (i.e., agent-experimenter-participant) performing goal-oriented actions in a classic false-belief scenario (i.e., change-of-location scenario).

In their experiment, Buttelmann et al. (2009) tested 16- and 18-month-olds. Infants first watched an agent placing a toy in either a right-side box or a left-side box. Then, in the false belief condition, the agent left the room. While the agent was away, an experimenter entered the room and moved the toy from one box to the other. Then, the experimenter showed the infants that the boxes could be locked using a pin. After locking the boxes, the experimenter left the room. When the agent returned, she unsuccessfully tried to pull the lid of the box where she stored the toy (see Figure 3.4).

Figure 3.4: ***Buttelmann, Carpenter, and Tomasello (2009): experimental setting.*** *The agent could place the toy in one of two different-coloured boxes. The lids of the boxes were locked with a black pin that could be seen only from the infant's point of view. Here the agent is unsuccessfully trying to open the lid of the empty box, right before the response period.*

16- and 18 month-olds infants did not help the agent with the box she was directly struggling with but instead crawled over the box actually containing the toy and unlocked it. In the true belief condition, although the agent did not leave the room during the change-of-location, she tried to open the box she knew was empty. In this case, 18-month-old infants (but not 16-month-old) chose to help her by unlocking the box she was directly struggling with (i.e. the empty box). Buttelmann and colleagues argue that this pattern of helping behaviour provides clear evidence that at least from 18-month-olds of age infants understand others' belief. According to the authors, infants in the false belief condition help retrieving the toy by opening the alternative box because they understand that if the other person is trying to open the box where she falsely believe the toy is located, then she must want the toy. Infants in the true belief condition help by opening the box the agent is struggling with because the reason that since she knows that the toy is in the other box, then she must have another reason for wanting to open that particular box.

In Experiment 1A, Experiment 1B and Experiment 2, I adapted the Buttelman et al.'s task to seek evidence of whether adult observers' false belief tracking could modulate the pre-reflective role played by the motor system in the course of participants' interaction with an agent. Since failures to conceptually replicate the original findings of Buttelmann et al. indicates that there is no normatively correct helping response to the task (Crivello & Poulin-Dubois, 2018; Fizke et al., 2017; Priewasser et al., 2018), I did not attempt to make any predictions about adults' final helping action. My overarching prediction focused instead on the different indicators of early action understanding. To this end, and differently from Buttelman and colleagues, I adopted a combination of eye-tracking, body-posture and mouse-tracking techniques to study early implicit belief-tracking and motor processes in the adult observer.

Testing adults with false-belief tasks that have been originally intended for studying young children or infants has sometimes received criticism because ”adults’ responses to false-belief scenarios may differ from those of infants for many reasons, including (a) adults are better able to generate explanations [...], and (b) adults’ greater knowledge about the world may lead them to perceive experimental displays differently” (Baillargeon et al. 2018, page 115). However, it is common in cognitive psychology to gather converging data across different age groups because similarities and differences in response profiles that persist despite differences in developmental stage can help define the diverse mental models characterising the psychological world that influence human’s behaviour (Samson & Apperly, 2010).

Once mindreading abilities are acquired sometimes in the course of the development, they are not fixed. They change across the lifespan (Happé, Winner, & Brownell, 1998), they are influenced by our choices (e.g., Kidd & Castano, 2013) and they can predict the quality of our social interactions in terms of interpersonal relationships (Castano, 2012) as well as prosocial behaviour (Johnson, 2012). Although studying adults is not easy because it requires rethinking tasks that have been traditionally developed to study children and infants, it is necessary for understanding interpersonal differences and to facilitate the construction of theoretical models (Apperly & Wang, 2021).

Mindreading has been traditionally studied to emphasise the acquisition of core concepts such as beliefs, desires and intentions, but research on theory of mind has traditionally neglected adults. Compared to others topics studied in developmental psychology, the mindreading field has in fact struggled to gather converging data across different age groups, partially because in standard mindreading tasks older children and adults show ceiling performance (Wellman et al., 2001). Some researchers have adapted classic tests for research with adult cohorts, for example by making the task for adults more complex (Baron-Cohen, Wheelwright, Hill, Raste, & Plumb, 2001; Birch & Bloom, 2007) than the ones intended for a younger population (Baron-Cohen et al., 1985; Ekman & Friesen, 1971). However, although testing adults using core mindreading concepts has sometimes been effective in revealing individual differences, for instance in diagnosis of ASD (e.g., Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001) or psychotic disorder (e.g., Guastella et al., 2013), it is difficult to retroactively pinpoint the exact cognitive mechanism at play in such complex tasks. Instead, by devising careful tasks it is possible to aim at isolating the different behavioural effects involved when adults engage in mindreading activity. My PhD thesis research contributes to that aim.

Developing an account of the mature system is not only intrinsically informative but it is also necessary to know the end point towards which the developmental process is directed towards. Since we can safely assume that adults possess fully fledged mindreading abilities, focusing on how the mature mindreader process the social world facilitates the understanding of individual differences and the construction of theoretical models that one can later use to conceptually compare to results obtained in younger populations (Apperly, 2010; Apperly, Back, Samson, & France, 2008; Apperly, Samson, & Humphreys, 2009; Samson

& Apperly, 2010). That is, ”to understand development it is useful to know what develops” (Apperly et al., 2009). The research with adults has moved towards this direction in the last 15 years, facilitating the emergence of new paradigms not focused on core concepts but rather on the underlying cognitive processes such as inference, storage and usage (Apperly & Wang, 2021; Apperly et al., 2009) and their relative automaticity (e.g., Samson et al., 2010; van der Wel et al., 2014).

In conclusion, the mindreading and the motor cognition field have traditionally approached the study of action observation using different experimental approaches which have led to the common assumption that the mindreading system is recruited when people reason about others' mental states in situations with little information about biological motion and that the mirror system enables the pre-reflective understanding of others' actions. However, the conjecture on the existence of a cognitively efficient belief-tracking process that influences the way by which the motorically grounded expectations are generated has recently sparkled interest in bridging the gap between the two approaches. Tasks measuring reaction times in adaptations of the ball detection task provide some initial support to the possibility of developing experimental paradigms that can convey bodily kinematics, and I am committed to viewing the interactive false belief scenario as presented in the Buttelman et al.'s helping task as having the untapped potential for documenting adults' spontaneous motor processing in the understanding of others' actions. On the one hand, its change-of-location component has the classic features which enable the study of mindreading abilities. On the other hand, the sequence of events are here presented in a scenario whereby the agent performs a reach-to-grasp action towards one of two objects (i.e., right box or left box) which, although unintended by the original authors, offers the possibility to test participants' spontaneous motor representations (as measured by means of their rightward-leftward leaning) reflecting action preparation of an agent who is about to reach for a right box as opposed to a left box.

Part II

The Experiments

Chapter 4

Experiment 1[1]

4.1 Experiment 1A

Experiment 1A sought to uncover evidence of whether adult observers' FB tracking could modulate the pre-reflective role played by the motor system in the course of participants' interaction with an agent.

I used an interactive helping task to service my investigation. In the classical version of the helping task (Buttelmann et al., 2009), participants observed an agent store an object inside box A. In the FB condition, while the agent was absent, an experimenter transferred the object into box B and then shut both boxes. In the true belief (TB) condition, the agent saw the experimenter move the object to box B. In both conditions, the agent approached the now-empty box (box A) and unsuccessfully tried to open it. The participants tested were 18-month-olds and 2.5-year-olds, and children's final helping action suggested some sensitivity to the agent's

[1] This chapter contains content written by Giovanni Zani from the following published article: Zani, Butterfill, and Low (2020)

belief about the content of the boxes: children opened the now-full box (box B) for the agent in the FB condition, and they opened the now-empty box for the agent in the TB condition. (This interpretation has been challenged by Priewasser et al. (2018) whose findings indicate that children's performance may be driven by tracking another's ignorance rather another's FB; this thesis' conclusion will not depend on which interpretation is correct.) I expanded the functionality of the task in two novel and theoretically grounded ways.

First, I measured adult observers' online belief-tracking in the helping task by outfitting participants with wearable eye-tracker glasses. Some studies contend that rapid tracking of others' beliefs can be under automated processes and can be reflected in anticipatory looking responses (Grainger et al., 2018). I should be careful to acknowledge, however, that eye movements can be controlled by multiple kinds of processes simultaneously (Low et al., 2016), with contributions from offline cognitive control (you can, for instance, move your eyes in response to instructions). The suggestion is merely that anticipatory eye movements-measured prior to the agent selecting a particular action-gives us a reasonable chance of picking up on FB tracking that may be underpinned by some cognitively efficient mindreading system. The prediction was that in the FB condition of the helping task, just before the agent is about to select an action, observers would look in anticipation towards the empty box. Similarly, in the TB condition, just before the agent selects an action, observers would look in anticipation towards the full box.

Second, I measured adult observers' motor-generated behavioural expectations by having participants stand on a Wii balance board (WBB), to provide temporally and spatially sensitive information about rapid changes in distribution of the body's centre of pressure in an online manner. Studies show that the WBB can reliably detect how motor representations activated during action observation and processing can elicit corresponding structures in motor control, resulting in unintended behavioural changes in motor output such as postural adjustments (Dijkstra, Eerland, Zijlmans, & Post, 2014; Jeannerod, 2006; Miles, Nind, & Macrae, 2010; Stins, Marmolejo-Ramos, Hulzinga, Wenker, & Cañal-Bruland, 2017). Studies also suggest that imagined movements produce subliminal electromyographic activity in the involved muscles and may be evidenced through perturbations in postural sway (Grangeon, Guillot, & Collet, 2011; Guillot et al., 2007). Such postural adjustments have been considered to reflect autonomic preparation occurring downstream from central motor planning (Boulton & Mitra, 2015; Collet, Di Rienzo, Hoyek, & Guillot, 2013). Leaning can provide a window into the unfolding of action prediction in observers' motor system, with leaning potentially being either a pre-reflective or spontaneous indicator of prediction generated at an early point. With respect to the helping task set-up where the agent's goal was to retrieve a target object, shifts in participants' mediolateral balance (leftwards–rightwards leaning) were of theoretical importance. I predicted that shifts in participants' leaning-sampled at an early time point when there were no overt cues to suggest which box the agent would ultimately choose to open-would pick up on FB tracking modulating motorically grounded expectations of the agent's actions. I specifically predicted that observers would lean in the direction they anticipate the agent will go, given her belief about the object location; observers would lean towards the empty box in the FB condition and lean towards the full box in the TB condition. However, if leaning reflects motorically grounded expectations of the agent's action that are independent from FB tracking, then observers would lean in the direction of the box containing the target object; observers would lean towards the full box in both the TB and the FB conditions.

Finally, though, what about later indicators of action understanding, particularly adults' final helping action? In other words, will adults' ultimate choice of action (either opening up the empty box or the full box) be the same as those of children in a Buttelmann et al. (2009) style of helping task? I do not think that this will necessarily be the case because there is no normatively correct helping response to the task (Andrews, 2012). This is indicated by failures to conceptually replicate the original findings of Buttelmann et al.; apparently irrelevant changes to the procedure, such as having children sit at a table, can affect whether a difference in the ultimate helping behaviour between the TB and FB conditions is observed (Crivello & Poulin-Dubois, 2018). Consequently, I did not attempt to make any predictions about adults' final helping action. I was, however, committed to viewing the helping task as having the untapped potential for documenting spontaneous motor processing in the understanding of others' actions. Consequently, my overarching prediction focused on the different indicators of early action understanding: I predicted that spontaneous leaning and gazing would overlap in response patterning, with both metrics foreshadowing prediction of the agent's action rather than the observer's action.

4.1.1 Wii Balance Board

The Wii Balance Board (WBB) (Nintendo, Kyoto, Japan) is a force platform included in the popular game Nintendo WiiFit. The WBB has been proven to be a reliable tool measuring temporally and spatially sensible information about the body's centre of pressure (COP) (Clark et al., 2010). The COP is defined as the orthogonal projection of the centre of gravity on a horizontal plane, and the WBB uses four sensors to express its mediolateral (i.e., left-right) position on the x-axis and anteroposterior (i.e., forward-backward) position on the y-axis in centimetres. For example, when a weight is perfectly distributed 50% on the left and 50% on the right, the resulting x-value recorded by the sensors of the WBB is equal to zero.

I used the WBB to measure participants' motor resonance during action observation in Experiment 1A, Experiment 1B and Experiment 2. At their core, these experiments were traditional False-Belief tasks with a change of location component: participants observed an agent who was going to perform an action the goal of which was to retrieve an object that was moved from one box to the other. The agent could either falsely or truly believe that the object was in the right-side box or in the left-side box. I was then able to investigate mediolateral shifts in balance posture exhibiting a lean towards the right-side box or towards the left-side box during the time of interest by calculating the average participants' COP displacement from the COP position at the beginning of the time of interest.

The WBB was connected to a computer via Bluetooth and a custom software (provided by Nathan van der Stoep at https://www.multisensoryspacelab.com/) was used to calibrate participants' baseline COP and to record their shifts in COP during the time of interest. The WBB acquires data at a refresh rate of 63 Hz on average and, like professional force platforms, suffers from high frequency noise (Audiffren & Contal, 2016). Therefore, the WBB data acquired in the experiments described below was post-processed by resampling at a stable 50 Hz and processed through an eight order Butterworth filter with a low-pass set at 12 Hz, as suggested by Clark et al., 2010.

4.1.2 Method

4.1.2.1 Participants

Buttelmann et al.'s (2009) interactive task, focused on differences in participants' final helping action, indicated that human beings from as young as 18-months of age respond differently when others have a true or a false belief about an object's location. Buttelmann et al.'s findings suggested that the interactive task could be suitably used with older participants; the task's effect size relating to, for example 2.5-year-olds' final helping action ($\chi(1, N = 24) = 8.22$, $p = .004$), was a large one at $W = 0.585$ (the square root of the chi-squared statistic divided by the sample size). Several recent studies (Crivello & Poulin-Dubois, 2018; Priewasser et al., 2018) have found that the differences in the ultimate helping behaviour between TB and FB conditions are difficult to replicate. Given the recent challenges over replication efforts, it was important to have power of .90 (rather than the conventional .80) to minimise the risk of failing to find any apparently real effect of differences in final helping action between the TB and FB conditions. G*Power 3.1 indicated that a sample size of 31 would be needed to reach the desired power of .90 for the Buttelmann et al. style of data characteristics (input: W = 0.585, error probability = .05; DF = 1). It has been noted by researchers (Crivello & Poulin-Dubois, 2018) that the Buttelmann et al. effect size was qualified by a high data exclusion rate; 54% of the total collected sample was eliminated for reasons such as participants' lack of cooperation, participants' refusal to touch or help open any box, or experimenter error. Being cautious to accommodate for a potentially high data exclusion rate as suggested by the original study would result in recruiting at least 16 more participants (0.54 x 31) to G*Power's sample size calculation, resulting in a minimum total sample of 47 participants. A total of 50 undergraduate students volunteered to take part in the current study that was advertised as an experiment on action observation for course credit. All participants were individually tested in a single-trial session. The data from 8 adults were excluded (16%) from formal data analyses due to actor error (3), experimenter error (2), or participants failing attention-memory checks in the post-experiment questionnaire (explained in the procedure section) (3). The final sample comprised of 42 adults (M = 19.2 years, range = 18 to 25 years, 32 females).

4.1.2.2 Procedure

The experimental room was prepared before each participant's arrival. A table was placed in the centre of the room. On the top of the table there were two boxes (each 10 cm height, 5 cm wide) and a pair of soundproof headphones connected to a mobile phone. The two boxes had a hidden unlocking mechanism: in order to open the lid, a push force had to be exerted on two specific corners of the top surface (see Figure 4.1 for a schematic representation of the experimental setting and the hidden unlocking mechanism). A fully functional WiiTM Balance Board (WBB) was placed 350 cm from the boxes and faced the front side of the table. A mock WiiTM Balance Board (mWBB) was positioned to face the opposite side of the table, 50 cm from the boxes.

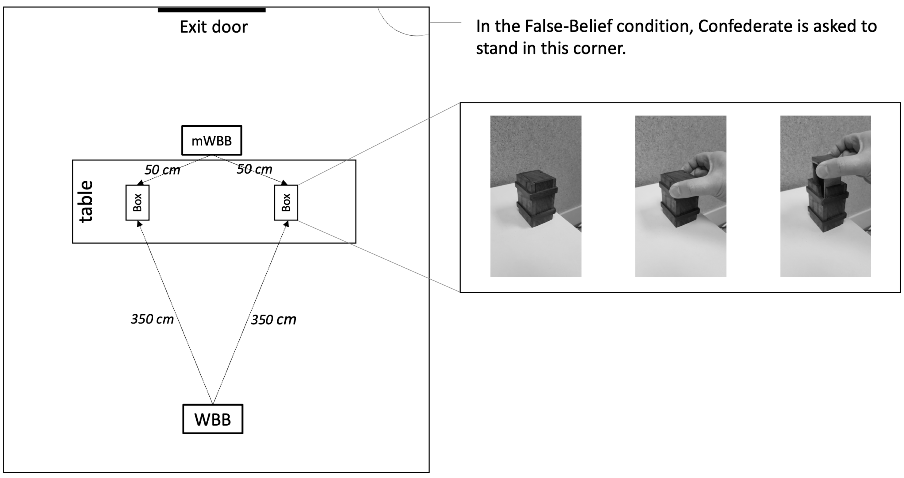


Figure 4.1: ***Experiment 1A: experimental setting***: *Schematic representation of the experimental setting and the boxes' unlocking mechanism adopted in Experiment 1A.*

After the participant signed the consent form, the experimenter indicated that a second participant was about to arrive (the second person was a confederate). In the meantime, the experimenter demonstrated how the boxes could be closed and opened. When the participant had successfully closed and opened the boxes, he or she was brought to stand on the platform (which was the fully functional WBB) facing the table. The experimenter helped the participant to wear the Tobii Pro Glasses 2 (i.e., wearable eye-tracker glasses), and then the experimenter performed Tobii Pro Glasses and WBB calibration (each device acquired information at 50 HZ sampling rate). The WBB was connected to a computer via Bluetooth and custom software was used to record body leaning. Gaze was recorded with Tobii Pro Lab. Synchronous recording of WBB and Tobii Pro Glasses data was managed by AutoHotkey V.1.1.29.01. As soon as the calibration procedure had been completed, the confederate knocked at the door. In order to strengthen the participant's conviction that the other person was a second participant, the experimenter showed the confederate where to leave her belongings, invited her to fill and sign the consent form, and then instructed her to stand on the platform (which was the mWBB) facing the other side of the table, and to wait until its calibration was completed.

While the confederate and the participant stood facing each other on their respective balance boards, the experimenter positioned himself between them (being careful to ensure that the participant's line of sight to both boxes was maintained). The experimenter's instructions to the confederate and the participant were as follows. "We are about to begin the experiment. Confederate (name used), I will ask you to perform some actions. Your task is to complete them but, if you need help, you can ask the other participant to come help you. Participant (name used), your task is to observe and, if the other participant asks for help, you have to go help her. Now we can begin the experiment. Confederate, do you have a small personal item such as a coin or a ring with you?" The confederate was trained to say, "Is this ring ok?" A scripted conversation then took place: the experimenter said, "It is perfect, can you put that ring in one of the two boxes?"; the confederate replied, "Either one?"; and the experimenter stated, "Yes". At this point the confederate put the ring in one of the two boxes (the initial location of the ring was counterbalanced throughout the experiment). The versions of what happened next differed according to the experimental condition. Each participant was assigned to either the false belief condition (FB) or to the true belief condition (TB).

For participants in the **FB condition**, the experimenter spoke aloud to the confederate as follows. "Now I am going to ask you to put the headphones on and to turn around towards this corner" (the experimenter showed the confederate that she would have had to step off the platform and to go to a corner of the room behind her, from which she could not see the table). "This is the sound you will be hearing on the headphones" (he played a loud white noise that could be heard clearly by the participant). "I will then leave the room and, as soon as you are ready, you have to close the door behind me and then you have to retrieve your object. Ok, now put the headphones on and go to the corner." Once the confederate faced the corner, the experimenter went to the table and moved the ring from one box (henceforth referred to as the now-empty box) to the other box (henceforth the now-full box) and then shut both boxes by pushing down on both lids. Then, the experimenter left the room using a door situated next to the corner that confederate was facing (see figure 1). After about 1000 ms, the confederate closed the door, turned around, walked towards the table and stepped back on the mWBB. For approximately 500 ms, the confederate maintained a gaze equidistant between the two boxes. Then the confederate oriented her gaze first towards the now-full box and then towards the now-empty box, and finally reached to open the latter. After about 2000 ms of unsuccessfully trying to open the now-empty box, the confederate assumed a neutral but natural position on the mWBB and asked the participant: ″Can you please help me?″ After the participant had helped to open a box, the confederate called the experimenter back into the room and the session ended.

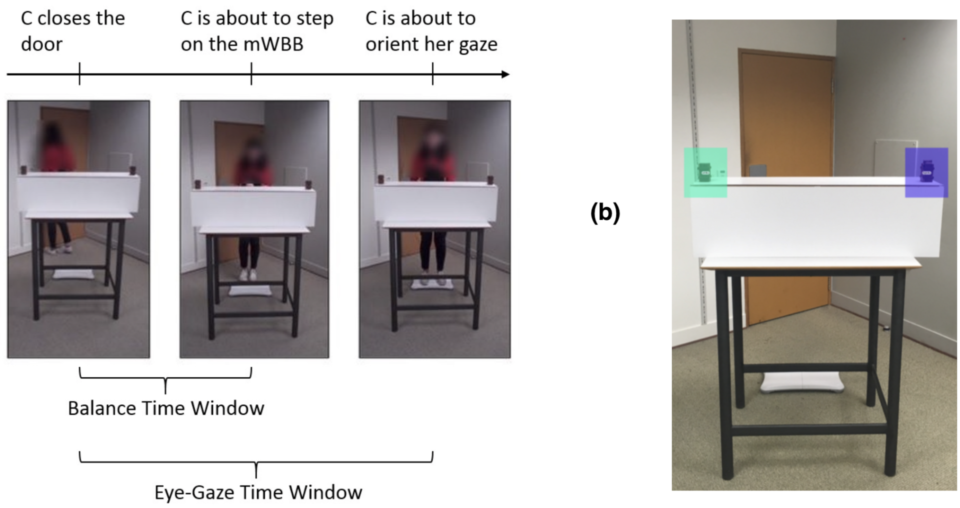
For participants in the **TB condition** the experiment spoke aloud to the confederate as follows. ″Now I am going to ask you to put the headphones on. This is the sound you will be hearing. I will then leave the room and, as soon as you are ready, you have to close the door behind me and then you have to retrieve your object. Ok, now put the headphones on.″ At this point, the experimenter went to the table and (watched by the confederate) he proceeded to move the ring from one box (the now-empty box), to the other one (the now-full box). Then the experimenter shut both boxes by pushing down both lids, and left the room. After about 1000 ms, the confederate stepped of the board, closed the door, turned around, walked towards the table and stepped back on the mWBB. After about 500 ms, the confederate oriented her gaze first towards the now-full box and then towards the now-empty box, and finally reached to open the latter. After about 2000 ms of unsuccessfully trying to open the now-empty box, the confederate assumed a neutral but natural position on the mWBB and asked the participant: ″Can you please help me?″ After the participant had helped to open a box, the confederate called the experimenter back into the room and the session ended.

At the end of the experimental session participants were invited to complete an exit questionnaire. There were 4 two-alternative forced-choice items providing checks on participants′ attention and memory. Each item showed a picture of the experimental table and boxes, and participants had to answer to the following questions: (1) ″Circle the box that the other participant placed her item into″; (2) ″Circle the box that the experimenter moved the item into″; (3) ″Circle the box that the other participant tried to open″; (4) Circle the box you went to open.″ If participants incorrectly answered one or more of the forced-choice attention and memory check items, their data would be excluded from formal analysis; the responses from 3 participants were excluded on this basis. The exit questionnaire also included two open-ended item probing for the reasons behind participants′ ultimate choice of helping action: ″Why did you go for that box?″ and ″Why didn′t you go for the alternative box?″ A final open-ended question probed whether participants happened to be familiar with or latched onto what the task was measuring by asking: ″What is the experiment about?″ None of the participants indicated familiarity with the task or its purpose; all participants merely indicated that the experiment was about action observation.

4.1.3 Results

Each participant's gazing (fixation duration to either box, first fixated box) was measured individually during a specific time of interest, beginning after the confederate closed the door and ending before she oriented her gaze towards one or the other box (see Figure 4.2 *(a)* for a schematic representation of the times of interest). Raw fixation durations were then transformed into proportions. To extract gaze data, I defined two same-sized (277 × 317 pixels) areas of interest (AOI, Figure 4.2 *(b)*)—the now-full box AOI and the now-empty box AOI—and applied the standard attention filter of the Tobii Pro Lab programme. In addition, I checked that participants' eye gaze was not followed by head/torso movements while fixating to one box or the other; this was done with the aim of excluding the possibility that participants' leaning could have been influenced by attention orientation.

(a)



(b)

Figure 4.2: ***Experiment 1A: times and areas of interest***: *(a) schematic of the selected times of interest. The balance time window had a fixed duration of 2020 ms, while the eye-gaze time window was selected individually for each participant (raw data were then transformed into proportions); (b) two same-size areas of interest (277 × 317 pixels) were selected for eye-gaze data analysis. The face of the confederate agent is blurred only for the purposes of this thesis and the original publication.*

As discussed in Section 4.1.1, the WBB has been proven to be a reliable tool providing temporally and spatially sensible information about the body's centre of pressure (COP) (Clark et al., 2010). I measured participants' average leaning on the WBB during a specific time of interest, beginning after the confederate closed the door and ending just before she stepped on the mWBB (See Figure 4.2). The time window for measuring participants' leaning ended just before the confederate stepped on the mWBB to avoid confounding effects that the confederate's action of stepping on the balance board (e.g. she raises one leg, she sways to restore the balance, she places her foot and so on) could have had on observers' own motor system. This time window was fixed for all participants and lasted 2020 ms; the trained confederate never took less than 2020 ms to go from the door to the balance board. The eye- gaze time window, however, included the moment when the confederate was on the mWBB and ended just before she oriented her gaze towards a box, to give us the best chance of detecting first fixations. In contrast with the consistent output from the balance board, some gaze-signal loss is inevitable due to the nature of eye tracking technology, and consequently, the eye-gaze time window was coded individually for each participant (and individuals' raw data were then transformed into proportions).

Finally, I also coded which box participants ultimately chose to help with (either by opening or touching).

For statistical analysis, IBM SPSS Statistics 24 was used. The significance level for all analysis was $p \leq 0.05$, two-tailed.

4.1.3.1 Eye Gaze analysis

A mixed analysis of variance with box (now-full, now-empty) as within-subjects factor and condition (FB, TB) as between-subjects factor was performed on the proportion of duration (in percentage) that participants (N = 42) spent fixating to either box. The results showed a significant interaction between box and condition ($F_{1,40} = 8.674$, $p = 0.005$, $\eta_p^2 = 0.178$). Specifically, post hoc comparisons revealed that participants in the TB condition fixated longer ($p = 0.022$, $\eta_p^2 = 0.125$) to the now-full box (M = 46.247; s.e. = 8.215; 95% CI: 29.643–62.852) compared to the now-empty box (M=16.253; s.e. = 8.018; 95% CI: 0.048–32.457) and that the now-full box was fixated longer (p = 0.009, η_p^2 = 0.159) by participants in the TB condition (M = 46.247; s.e. = 8.215; 95% CI: 29.643–62.852) compared to participants in the FB condition (M = 11.715; s.e. = 9.486; 95% CI: -7.458 to 30.888) (Figure 4.3).

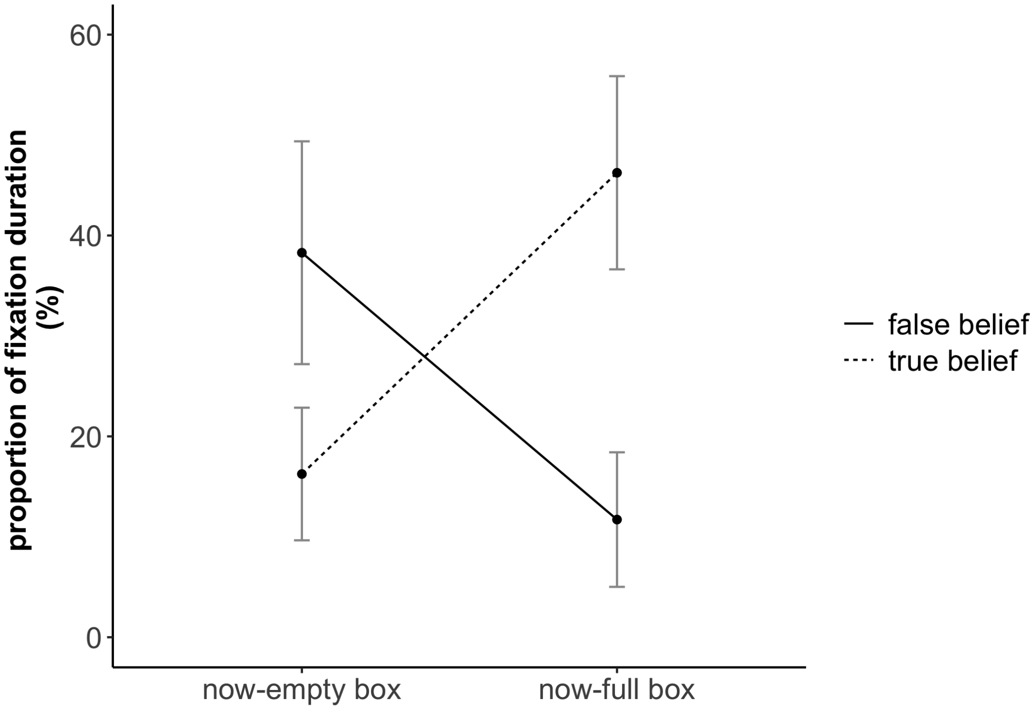


Figure 4.3: ***Experiment 1A: Fixation Duration.*** *Fixation Duration (in %) on each box (now-empty, now-full) in FB and TB conditions.*

With respect to first looks, 24 participants (57%) showed a clear first fixation to either the now-empty box or the now-full box in the specific time window of interest; all of these participants were gazing at the confederate's hand at the beginning of the critical time window, so their first fixations were not the result of them already looking at one or the other box. The remaining 18 participants (43%) did not show any first looks to either box during the specific time window, either because they looked anywhere outside the selected AOIs (11 participants) or because the eye-movements signal was lost (7 participants). Among the 24 participants who did show a first fixation, no significant effects emerged from the Fisher exact test to determine whether there was any relationship between condition (FB, TB) and the box (now-full box, now-empty box) that was first fixated upon (Fisher exact test, $p = 0.241$) (Figure 4.4).

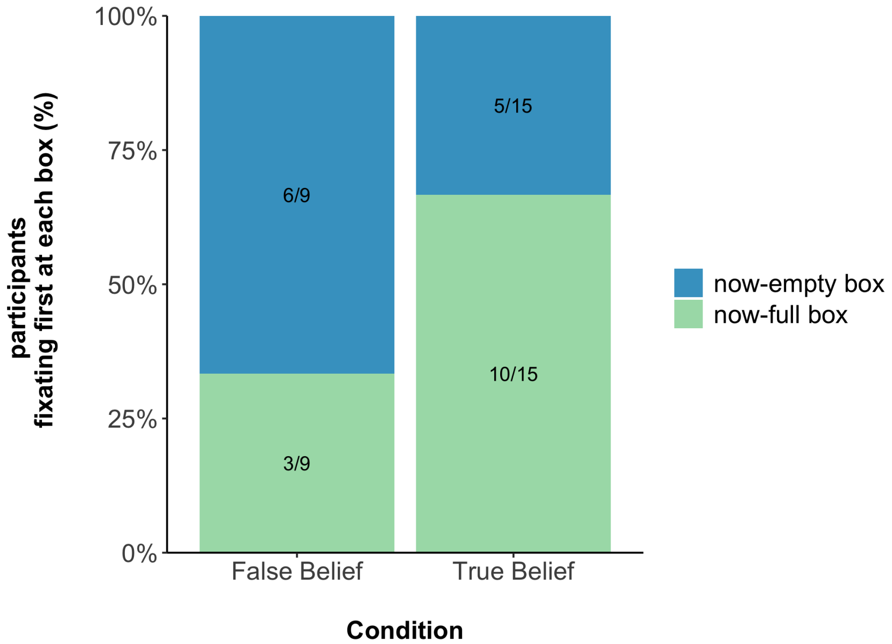


Figure 4.4: ***Experiment 1A: First Fixation.*** *Number of participants fixating first at either the now-empty box or the now-full box during the critical time window (N=24) by condition (FB or TB).*

4.1.3.2 Balance analysis

I next examined participants' mediolateral leaning on the WBB (*N* = 33/42; balance board data of four participants were not acquired due to technical problems; balance board data of four participants were excluded for exceeding the mean more than 2 s.d. A Mann–Whitney *U*-test was conducted to determine whether there was a difference in the average leaning between those assigned to the FB condition and those assigned to the TB condition. Results revealed a significant group difference (Mann-Whitney $U = 67$, $p = 0.012$), with participants in the FB condition leaning towards the now-empty box (M = -0.09, s.d. = 0.21, CI = -0.56, 0.18) and participants in the TB condition leaning towards the now-full box (M = 0.07, s.d. = 0.14, CI = -0.25, 0.30) (see Figure 4.5).

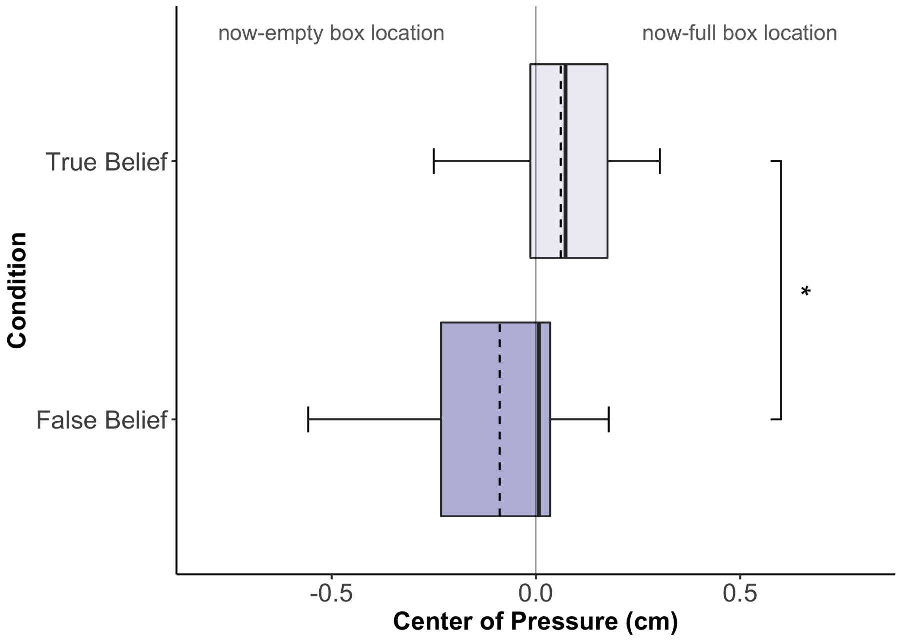


Figure 4.5: ***Experiment 1A: Boxplots of displacement from body midline.*** *Graphical representation of displacement from body midline (0) split for group (FB, TB). Positive values reflect a leaning towards the box with the object in it (now-full box); negative values reflect a leaning towards the box in which the object was initially located (now-empty box). Dotted line in the box represents the mean, continuous line represents the median, length of the box represents the interquartile range and the whiskers extend to the highest and lowest observations.*

4.1.3.3 Final Helping behaviour analysis

A χ^2 test, performed on which box participants chose to help with (either by opening or touching), showed that final helping action was not significantly different between conditions ($\chi^2(1, N{=}42){=}\ 0.146$, p = 0.703, Figure 4.6). In general, most participants (N = 36/42, 86%) decided to help with the box that the confederate agent was struggling to open (i.e., the now-empty box in the FB and in the TB conditions, 83% and 87%, respectively). The percentages of participants selecting to help open the now-empty box in the FB and TB conditions were different from chance by a binomial test (p = 0.003 with Cohen's g = 0.33, and p = 0.001 with Cohen's g = 0.37, respectively). Further, no significant effects emerged from a Fisher exact test that I ran to investigate whether there was any relation between the first fixated box and the box participants ultimately chose to help with (Fisher exact test, p = 0.634).

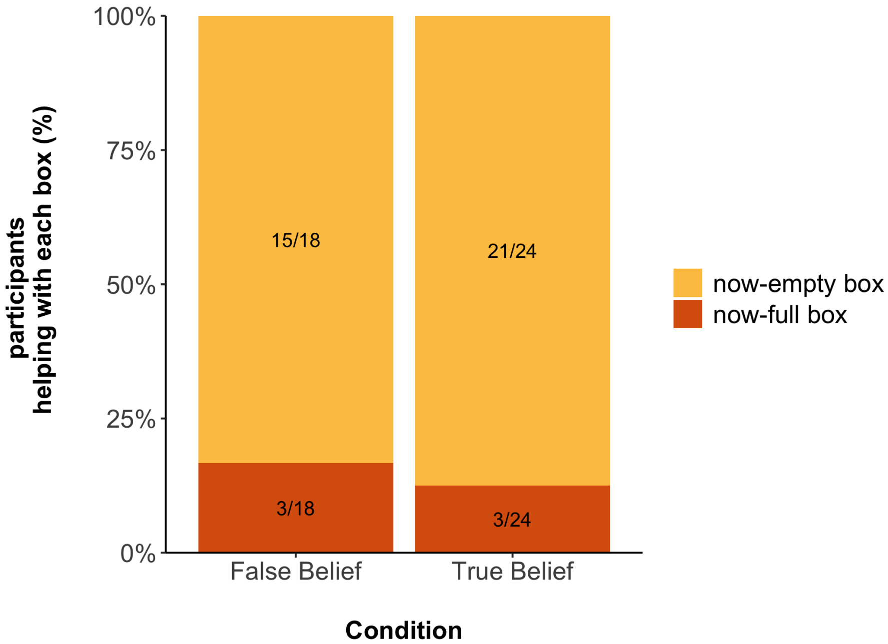


Figure 4.6: ***Experiment 1A: Helping Behaviour.*** *Number of participants who helped with either the now-empty box or the now-full box (N=42) by condition (FB or TB).*

I analysed the reasons participants offered for their final helping action. Following a common practice in theory-of-mind studies that work with narrative-based or categorical responses (Fizke et al., 2017; Lecce et al., 2019), two raters independently coded 24% (*n*=10) of participants' reasons for their final helping action, given to question #1 (Explain why you went to that box) and question #2 (Explain why you didn't go to the alternative box). Both raters were blind to the condition (TB or FB) that the participants' answers belonged to. The raters independently coded the explanations into one of three categories. One category picked up on matters of fact (e.g. 'Because that was [the box] that wasn't being used';

'It was the box that the item was originally placed in'). Another category picked up on explanations that referred to someone's general ability to try to open a box (e.g. 'This was the one she was struggling with'; 'Because it was the other box that the person was having trouble with'). The final category picked up on any mental states relating to desires, knowledge, perceptions or thoughts (e.g. 'Because I need to help get the item and I know it was in that box'; 'Because I was helping the person open the box they thought the item was in'). The average of the two raters' classifications of the participants' explanations produced an inter-correlation coefficient of 0.91, $p<0.001$, which represented excellent reliability. One of the raters then coded the remaining explanations. The results were straightforward. Most participants in the TB condition (83%, n=19/23) and FB condition (72%, n=13/18) referred to facts or the agent's general ability to open a box when explaining why they went to help open the now-empty box (e.g. 'They were struggling with that box, so I showed them how to do it') (see Table 4.1 for a summary of participants' explicit reasoning).

Many participants in the TB condition who opened the now-empty box (65%, 15/23) also talked about facts or the agent's general ability when explaining why they did not open the alternative (now-full) box (e.g. 'It felt more natural to walk over to where the person was standing'; 'Because the person was not trying to open that one'). With respect to those participants opening the now-empty box in the FB condition, the participants provided fact- or ability-based explanations (53%, 8/15) or mental-state explanations (47%, 7/15) for not opening the alternative (now-full) box. Those mental-state explanations could suggest that some

Table 4.1: *Experiment 1A: Numbers of participants in the TB and FB conditions (n = 23 and n = 18, respectively) who provided fact-based, ability-based or mental-state-based reasons for the questions that sought explanations of why they went to open one box and did not go to open the alternative box. One participant in the TB condition did not answer these questions, and hence the coding of reasons in TB condition was based on data from 23 participants.*

	Those who opened now-empty box			**Those who opened now-full box**		
Reason:	fact	ability	mental state	fact	ability	mental state
Question 1: Explain why you went to that box						
TB	8	11	1	0	0	3
FB	2	11	2	1	0	2
Question 2: Explain why you didn't go to the alternative box						
TB	10	5	5	1	0	2
FB	4	4	7	2	0	1

adults may also not necessarily use their ability to rapidly track belief for personally correcting an agent's false-belief during the final helping action.

4.1.4 Discussion

Experiment 1A confirmed adult observers' FB tracking ability as manifested in certain anticipatory gaze response patterns. In the FB condition, just before the agent was about to select an action, participants looked in anticipation towards the empty box. Correspondingly, in the TB condition, just before the agent was about to select an action, participants looked in anticipation towards the full box. These results dovetail with those studies showing that specific eye gazing can reveal adults' ability to quickly and correctly anticipate the action of a person who has an FB or a TB about the location of an object (Grainger et al., 2018; Priewasser et al., 2018).

The analyses of adults' mediolateral balance shifts-sampled at an early time point in the event sequence when there were no overt cues to suggest which box the agent would move towards-confirmed spontaneous motor representation of belief-based actions by the observers in response to the agent's predicament. In the FB condition, adults leaned towards the empty box; and in the TB condition, they leaned towards the full box. These results document, for the first time, adults' motorically grounded expectations of the agent's action being modulated by the workings of an FB tracking system. These results suggest that motor representations and processes can go beyond mere goal ascription; they can successfully accommodate cases where belief-tracking informs goal ascription.

In Experiment 1A, adults' final helping actions were unlike those which have been reported for young children in a similar helping task (Buttelmann et al., 2009). Adults (different from young children) were not more likely to help open the now-full box in the FB condition than in the TB condition. The majority of adults helped to open the now-empty box in both conditions. When I asked them why they chose this box, adults generally referred to facts relating to the situation or to the agent's abilities, rather than to mental states per se.

Why did the final helping response not reflect belief information that adults' eye gaze and leaning responses picked up upon? One possibility is that adults are poor at reflecting on the agent's belief in the course of socially interacting with her, despite the occurrence of FB tracking. Much as adults have been shown to not always put to use another's visual perspective when interacting with her (Keysar, Lin, & Barr, 2003), so also they may cut corners by ignoring another's belief. Importantly, my results indicate that they could be doing this even when their eye gaze and leaning indicate that they have tracked the belief: if so, there may be a dissociation in adults' performance analogous to that sometimes observed in young children (Clements & Perner, 1994; Low & Watts, 2013; Ruffman, Garnham, Import, & Connolly, 2001). Alternatively, it may be that adults had the agent's mental state in mind all along but took the view it was normatively irrelevant to their choice of action. This possibility is consistent with the observation that no adults expressed the view that their choice of final helping action was mistaken when subsequently asked why they had acted as they did.

4.2 Experiment 1B

Building from Experiment 1A's methodology and procedure, Experiment 1B was conceived to account for why, despite showing sensitivity to belief in eye gaze and leaning, adults did not take belief into account in their final helping actions. Two situational motivators were introduced to increase the likelihood of explicit mindreading and to make the agent's belief normatively relevant for participants' helping behaviour. First, I provided a clear introductory example (without giving away the false/true belief component) of the chain of inferences that could later lead the agent to open the now-full box as opposed to the now-empty box. In fact, manipulating overt instructions to enable participants' understanding of what is required in the task has been proven to be a suitable motivator in getting adults to take others' perspective in cognitively effortful scenarios (Wang, Ciranova, Woods, & Apperly, 2020). Second, I introduced a reward (i.e., a candy) that could be obtained when performing an helping behaviour that was in accordance with the instructions. The external reward, beside contributing to elicit explicit mindreading, was aimed at providing a normatively relevant way to perform the task.

In Experiment 1B, I predicted that the introduction of external situational motivators would preserve adults' ability to spontaneously look in anticipation of and to motorically represent the action of the agent while also eliciting a final helping response that reflected the belief information.

4.2.1 Method

4.2.1.1 Participants

As described in section 4.1.2.1, G*Power 3.1 indicated that a sample size of thirty-one would be needed to reach the desired power of .90 for the Buttelmann et al. (2009) style of data characteristics (input: W = 0.585, error probability = .05; DF = 1). Five additional participants would also be needed to accommodate for the exclusion rate (16%) registered in Experiment 1A (.16 x 31) resulting in a minimum total sample of thirty-six participants. Forty-two students participated in this experiment for course credit and they were individually tested in a single-trial session. Three participants were excluded from all data analysis because of actor error (1) or failure to understand instructions as assessed in a post-experiment questionnaire (2). Additionally, balance board data of seven participants and gaze data of one participant was not acquired due to technical problems. The final sample comprised of 39 adults (M = 19.7, range = 18-41, 29 female)

4.2.1.2 Procedure

The materials and apparatus were the same as in Experiment 1A with the addition of two elements: i) a candy was placed on the table between the two boxes; ii) a bag containing nine yellow cards and one blue card was placed on a shelf out of the participant's line of sight. While in Experiment 1A the confederate was instructed to put a personal belonging in one of the two boxes, in Experiment 1B she was asked to put the candy in it. In Experiment 1B, the confederate was also instructed to later open the box with the candy in it or the empty box based on the colour of the card she was asked to draw from the bag. The first part of the procedure was the same as in Experiment 1A (section 4.1.2.2) and is reported here for convenience. After the confederate had put the candy in one of the two boxes, the procedure changed according to the experimental condition.

As in Experiment 1A, after the participant signed the consent form, the experimenter indicated that a second participant was about to arrive (the second person was a confederate). In the meantime, the experimenter demonstrated how the boxes could be closed and opened. When the participant had successfully closed and opened the boxes, he or she was brought to stand on the platform (which was the fully functional WBB) facing the table. The experimenter helped the participant to wear the Tobii Pro Glasses 2 (i.e., wearable eye-tracker glasses), and then the experimenter performed Tobii Pro Glasses and WBB calibration (each device acquired information at 50 HZ sampling rate). The WBB was connected to a computer via Bluetooth and a custom software was used to record body leaning. Gaze was recorded with Tobii Pro Lab. Synchronous recording of WBB and Tobii Pro Glasses data was managed by AutoHotkey V.1.1.29.01. As soon as the calibration procedure had been completed, the confederate knocked at the door. In order to strengthen the participant's conviction that the other person was a second participant, the experimenter showed the confederate where to leave her belongings, invited her to fill and sign the consent form, and then instructed her to stand on the platform (which was the mock WBB;

mWBB) facing the other side of the table, and to wait until its calibration was completed.

While the confederate and the participant stood facing each other on their respective balance boards, the experimenter positioned himself between them (being careful to ensure that the participant's line of sight to both boxes was maintained). The experimenter's instructions to the confederate and the participant were as follows. "We are about to begin the experiment. Confederate (name used), I will ask you to perform some actions. Your task is to complete them but, if you need help, you can ask the other participant to come help you. Participant (name used), your task is to observe and, if the other participant asks for help, you have to go help her. Now we can begin the experiment. Confederate, could you please put this candy (the experimenter place a candy in on the table between the two boxes) in one of the two boxes?". The confederate was trained to say, "Sure. Either one?" The experimenter replied, "Yes". At this point the confederate put the candy in one of the two boxes (the initial location of the candy was counterbalanced throughout the experiment). The versions of what happened next differed according to the experimental condition. Each participant was assigned to either the false belief condition (FB) or to the true belief condition (TB).

For participants in the **FB condition** E said to C: "Now I am going to ask you to put the headphones on and to turn around towards this corner." E showed C that she would have to step off the mWBB and to go to a corner of the room behind the mWBB, from which she could not see the table. Then C was told, "This is the sound you will be hearing." E played a loud white noise that could be heard by the participant. "I will then leave the room and, as soon as you are ready, you have to close the door behind me and then you have to open either the box with the candy or the empty one." E grabbed a little bag from a shelf. "You have to open the box with the candy if you draw a yellow card. You have to open the empty box if you draw a blue card." E emptied the content of the bag on the table, making sure that it was visually available to both C and the participant. "As you can see there are 9 yellow cards and just 1 blue card." E put the cards back into the bag. "Now, draw a card, look at the colour without showing it to the other participant and put it in a pocket." C drew a card and put it in her pocket. "Ok, now put the headphones on and go to the corner. Remember, if you drew one of the yellow cards, you have to open the box with the candy, if you drew the blue card, you have to open the empty box. Also, you can open only one box. If the correct box is opened, the one matching the colour, you will both get a candy as a reward." After the confederate had reached the corner while facing the wall, E went to the table, moved the candy from one box to the other one and then shut the boxes by pushing down the lids. Then, E left the room using a door situated next to the corner that C was facing. After about 1000 ms, C closed the door, turned around, walked towards the table and stepped back on the mWBB. For approximately 500 ms C maintained a gaze equidistant between the two boxes. Then C oriented her gaze first towards the now-full box and then towards the now-empty box, and finally reached to open the latter. After about 2000 ms of unsuccessfully trying to open the now-empty box, C assumed a neutral but natural position on the mWBB and asked the participant: "Could you please help me?"

Since the other person is trying to open the box where she falsely believes the candy is located, that means that the card she drew at the beginning of the experiment indicated to open the box with the candy in it. Here, from the participants' point of view, the reward is achieved if they help in opening the box that is actually containing the candy.

For participants in the **TB condition** E said to C: "Now I am going to ask you to put the headphones on. This is the sound you will be hearing." E played a loud white noise that could be heard by the participant. "I will then leave the room and, as soon as you are ready, you have to close the door behind me and then you have to open either the box with the candy or the empty one." E grabbed a little bag from a shelf. "You have to open the box with the candy if you draw a yellow card. You have to open the empty box if you draw a blue card." E emptied the content of the bag on the table making sure that it was visually available to both C and the participant. "As you can see there are 9 yellow cards and just 1 blue card." E put the cards back into the bag. "Now, draw a card, look at the colour without showing it to the other participant and put it in a pocket." C drew a card and put it in her pocket. "Ok, now put the headphones. Remember, if you drew one of the yellow cards, you have to open the box with the candy, if you drew the blue card, you have to open the empty box. Also, you can open only one box. If the correct box is opened, the one matching the colour, you will both get a candy as a reward." At this point, E went to the table, he moved the candy from one box to the other one and then shut the boxes by pushing down the lids. Then, E left the room using a door located behind C. After about 1000 ms, C closed the door, turned around, walked towards the table and stepped back on the mWBB. For approximately 500 ms C maintained a gaze equidistant between the two boxes. Then, after about 500 ms, C oriented her gaze first towards the now-full box and then towards the now-empty box, and finally reached to open the latter. After about 2000 ms of unsuccessfully trying to open the now-empty box, C assumed a neutral but natural position on the mWBB and asked the participant: “Could you please help me?”

Since the other person knows where the candy is locate and is trying to open the empty box, that means that the card she drew at the beginning of the experiment indicated to open the box without the candy in it. Here, from the participants point of view, the reward is achieved if they help in opening the empty box.

At the end of the experiment, participants' were requested to fill the same post-experiment questionnaire as in Experiment 1A, to which three control questions were added: Q1) “How many yellow cards were in the bag?” (Correct answer: ”9”); Q2) “How many blue cards were in the bag?”(Correct Answer: ”1”); Q3) “In what case were you and the other participant going to get a candy as a reward?” (A correct answer had to be of the like of: ”if the box matching the card rule is opened”). All participants included in the study understood and remembered the instructions, as indicated by their accurate responses to the control questions.

4.2.2 Results

Data analysis was performed as for Experiment 1A.

4.2.2.1 Eye Gaze analysis

The eye-tracking data of three participants was not acquired due to equipment malfunction. The eye gaze data analysis was performed on a sample of N = 36. A mixed analysis of variance with box (now-full, now-empty) as within-subjects factor and condition (False-Belief, True-Belief) as between-subjects factor was performed on the proportion of duration (in percentage) that participants (N = 36) spent fixating to either box. No significant main effect for Box ($F_{(1,36)}$ = 1.437, p = .238, η_p^2 = .038) and Condition ($F_{(1,36)}$ = 1.279, p = .266, η_p^2 = .034) nor significant interaction between Box and Condition($F_{(1,36)}$ = 3.701, p = .062, η_p^2 = .093) emerged from the mixed ANOVA on Fixation Duration with Box (now-full, now-empty) as within-subjects factor and Condition(False-Belief, True-Belief) as between-subjects factor (see Figure 4.7).

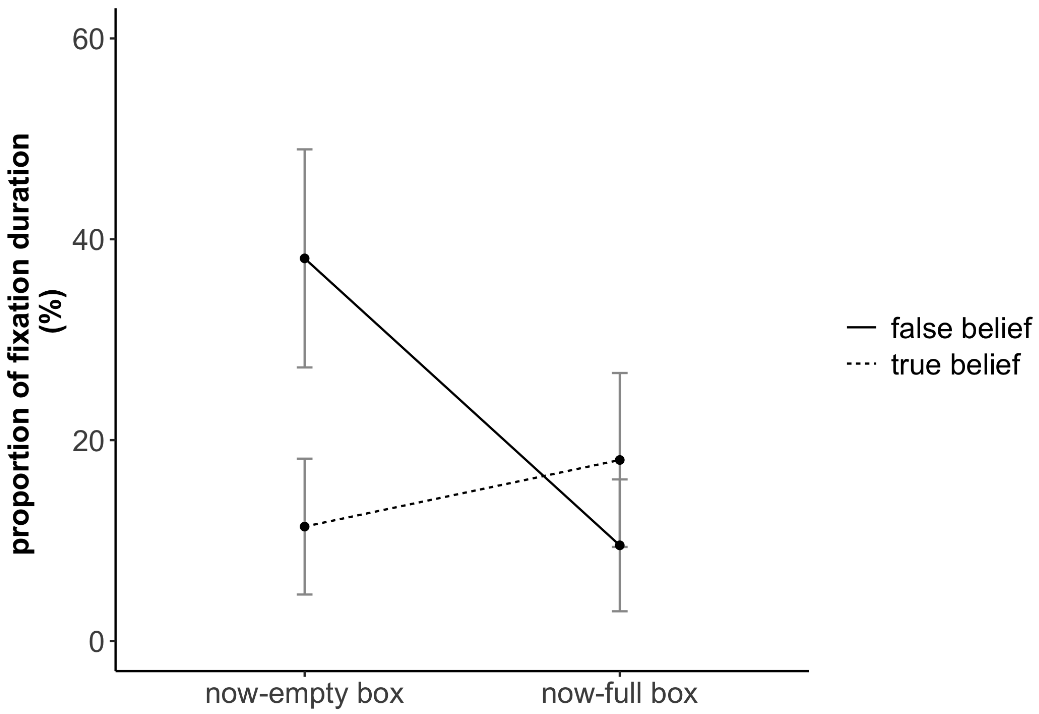


Figure 4.7: ***Experiment 1B: Fixation Duration.*** *Fixation Duration (in %) on each box (now-empty, now-full) in FB and TB conditions.*

With respect to first looks, 15 participants (42%) showed a clear first fixation to either the now-empty box or the now-full box in the specific time window of interest; all of these participants were gazing at the confederate's hand at the beginning of the critical time window, so their first fixations were not the result of them already looking at one or the other box. The remaining 21 participants (58%) did not show any first looks to either box during the specific time window, either because they looked anywhere outside the selected AOIs (15 participants) or because the eye-movements signal was lost (6 participants). Among the 15 participants who did show a first fixation, no significant effects emerged from the Fisher exact test to determine whether there was any relationship between condition (FB, TB) and the box (now-full box, now-empty box) that was first fixated upon. No significant effects emerged from the Fischer Exact test between Condition and First Fixated Box (Fischer Exact test, p = .089; see Figure 4.8).

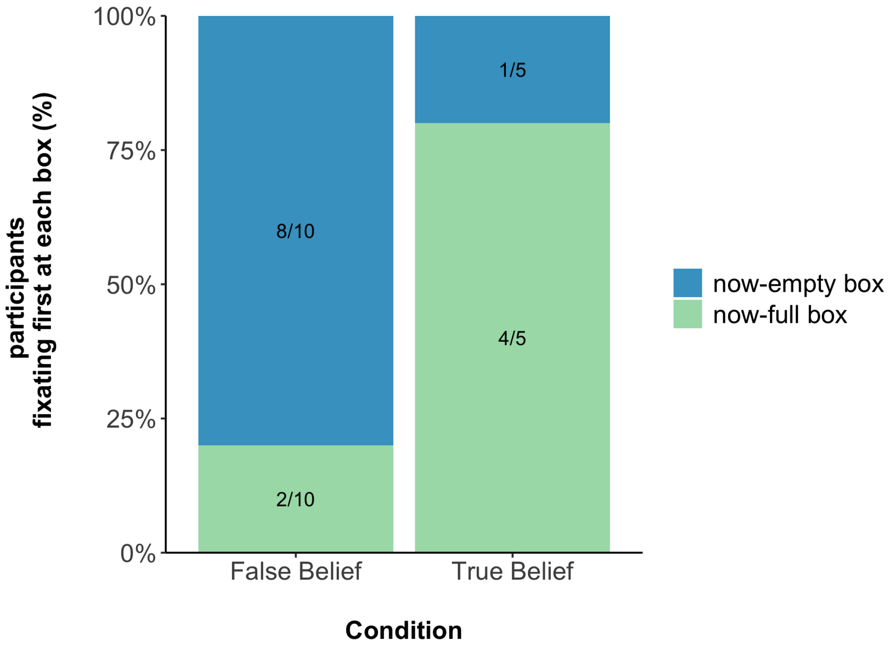


Figure 4.8: ***Experiment 1B: First Fixation.*** *Number of participants fixating first at either the now-empty box or the now-full box during the critical time window (N=15) by condition (FB or TB).*

4.2.2.2 Balance analysis

I next examined participants' mediolateral leaning on the WBB (N = 31/42; three participants were excluded from all the analysis; balance board data of seven participants were not acquired due to technical problems; balance board data of one participants were excluded for exceeding the mean more than 2 s.d. No significant effect emerged from the Mann-Whitney U test on average leaning between conditions (Mann-Whitney U = 93, p = .337. In particular, participants' average leaning seems to overlap across False-Belief condition (M = -0.001, SD = 0.17, CI = -0.09, 0.08) and True-Belief condition (M = -0.07, SD = 0.16, CI = -0.17, 0.03) (see Figure 4.9).

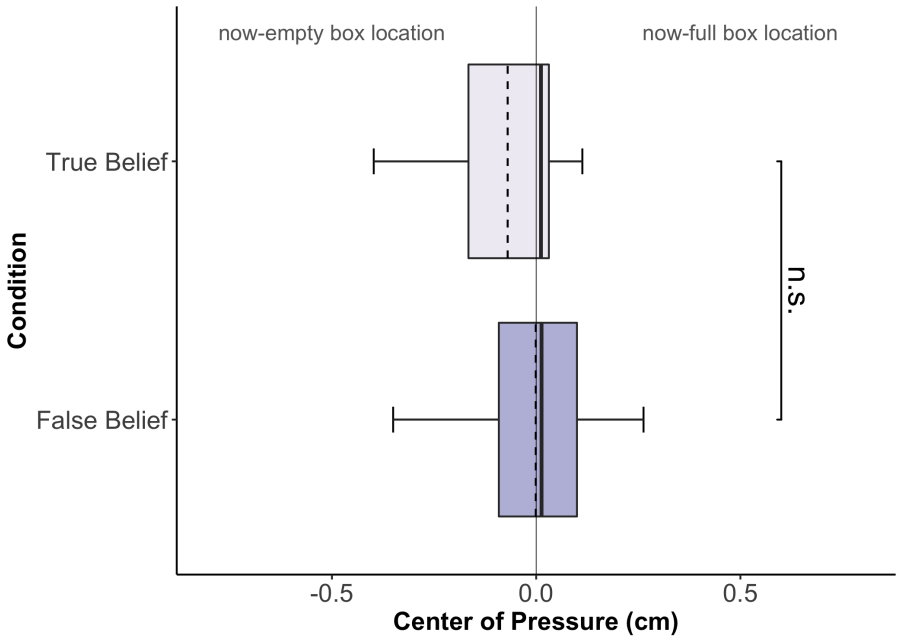


Figure 4.9: ***Experiment 1B: Boxplots of displacement from body midline.*** *Graphical representation of the non-significant difference of displacement from body midline (0) between groups (FB, TB). Positive values reflect a leaning towards the box with the object in it (now-full box); negative values reflect a leaning towards the box in which the object was initially located (now-empty box). Dotted line in the box represents the mean, continuous line represents the median, length of the box represents the interquartile range and the whiskers extend to the highest and lowest observations.*

4.2.2.3 Final Helping behaviour analysis

Participants' final helping behaviour was not significantly different between conditions, as indicated by a χ^2 test performed on which box participants chose to help with (either by opening or touching) [χ^2 (1, N =

39) = 3.444, p = .063; see Figure 4.10]. In general, in line with Experiment 1A, most participants (N = 35/39, 90%) decided to help with the box that the confederate agent was struggling to open (i.e., the now-empty box in the FB and in the TB conditions, 81% and 100%, respectively). The percentages of participants selecting to help open the now-empty box in the FB and TB conditions were different from chance by a binomial test (p = 0.004 with Cohen's g = 0.31, and $p<0.001$ with Cohen's g = 0.5, respectively). Furthermore, the non-significant Fischer Exact test performed between First Fixated Box and Helping Behaviour (Fischer Exact test, p = .229) suggests a lack of relation between the first fixated box and the box participants ultimately chose to help with.

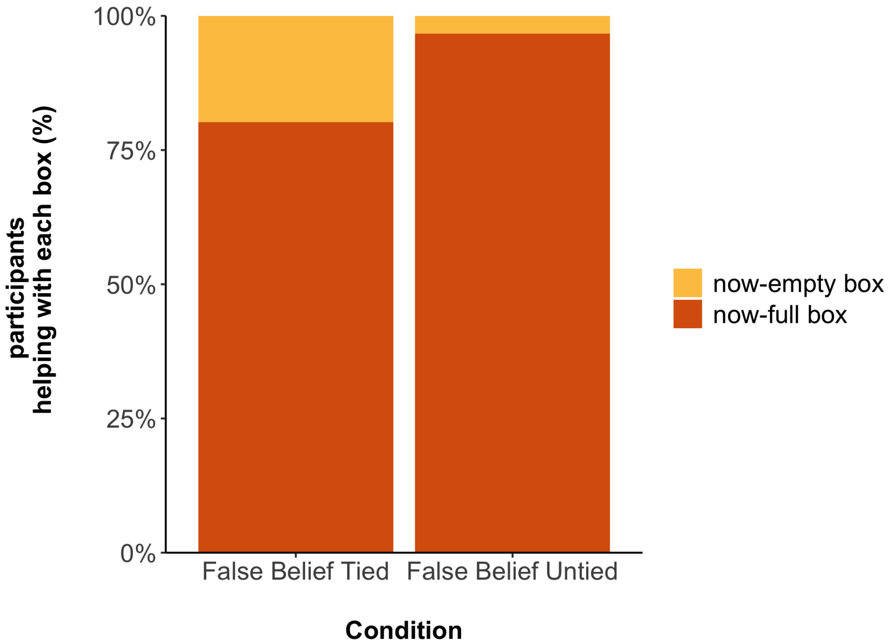


Figure 4.10: ***Experiment 1B: Helping Behaviour.*** *Number of participants who helped with either the now-empty box or the now-full box (N=39) by condition (FB or TB).*

I analysed the reasons participants offered for their final helping action. Following a common practice in theory-of-mind studies that work with narrative-based or categorical responses (Fizke et al., 2017; Lecce et al., 2019), two raters independently coded 26% (n=10) of participants' reasons for their final helping action, given to question #1 (Explain why you went to that box) and question #2 (Explain why you didn't go to the alternative box). Both raters were blind to the condition (TB or FB) that the participants' answers belonged to. The raters independently coded the explanations into one of three categories. One category picked up on matters of fact (e.g. 'Because it was the box she chose to open'; 'It was the box that she initially put the candy in'). Another category picked up on explanations that referred to someone's general ability to try to open a box (e.g. 'she tried to open that box but she couldn't'; 'Because I knew how to open that box'). The final category picked up on any mental states relating to desires, knowledge, perceptions or thoughts (e.g. 'Because the other participant thought the candy was in the box where she put it therefore I assumed that she got a yellow card and was trying to get the candy'; 'she wasn't aware of the change'). The average of the two raters' classifications of the participants' explanations produced an inter-correlation coefficient of 0.9, $p<0.001$, which represented excellent reliability. One of the raters then coded the remaining explanations. Most participants in the TB condition (82%, n=14/17) and FB condition (73%, n=16/22) referred to facts or the agent's general ability to open a box when explaining why they went to help open the now-empty box (e.g. 'They were struggling with that box, so I showed them how to do it') (see Table 4.2 for a summary of participants' explicit reasoning).

Table 4.2: *Experiment 1B: Numbers of participants in the TB and FB conditions (n = 17 and n = 22, respectively) who provided fact-based, ability-based or mental-state-based reasons for the questions that sought explanations of why they went to open one box and did not go to open the alternative box.*

	Those who opened now-empty box			Those who opened now-full box		
Reason:	fact	ability	mental state	fact	ability	mental state
Question 1: Explain why you went to that box						
TB	14	3	0	0	0	0
FB	16	2	0	1	2	1
Question 2: Explain why you didn't go to the alternative box						
TB	16	1	0	1	0	2
FB	16	0	2	2	0	2

4.2.3 Discussion

Similar to Experiment 1A, adults' final helping actions in Experiment 1B differed from those reported with young children by Buttelmann et al. (2009). The majority of adults helped to open the now-empty box in both conditions even though they knew it was wrong to do so if they wanted to achieve the reward in the False Belief condition. In fact, when I asked them to indicate the case in which they and the confederate would have achieved the reward, all participants (except for two, who were excluded from all data analysis) correctly indicated that (as per instructions) they were going to get the candy by opening the box that matched the colour of the card drawn by the confederate at the beginning of the trial. That is, in the false-belief condition, the confederate trying to open the box she falsely believed contained the candy meant that she picked a card indicating to retrieve the candy, and participants should have opened the full-box to get the reward. However, participants reported that they chose the empty box because of facts relating to the situation or to the confederate's abilities, rather than to her mental states. As discussed for Experiment 1A, one possibility is that adults sometimes don't use another's visual perspective during a social interaction (Keysar et al., 2003), and they could do so even when it is against the mutual interest of achieving a reward. In particular, in Experiment 1B, they could have regarded the agent's perspective as irrelevant because they interpreted the instruction to help as in to help with what the agent was directly struggling with (i.e., the empty box) and not with the ultimate goal of achieving the reward. Alternatively, it might be that someone else attending to a specific object attracts the observer's attention (Bukowski, Hietanen, & Samson, 2015) and spontaneously generates new motor representations for goals related to that particular object (Rizzolatti & Craighero, 2004) regardless of one's initial anticipation of how the events would unfold. That is, it might be that participants in Experiment 1B initially took the view it was normatively correct to help by opening a box with the goal of achieving the reward, but that the association agent-empty-box just before response time overrode what they initially thought was the correct way to help.

Further, Experiment 1B did not confirm adults' anticipatory gaze response patterns that I found in Experiment 1A, and the analyses of adults' mediolateral balance shifts did not reflect spontaneous motor representation during the observation of an agent's belief-based actions. These results are not surprising when considering the recent unsuccessful attempts to use implicit measures to test fast belief-tracking abilities (e.g., Dörrenberg et al., 2018; Kulke et al., 2018; Schuwerk, Priewasser, Sodian, & Perner, 2018). It is possible that implicit mindreading is not as robust as previously thought and that its existence needs further empirical support to be clarified (Kulke, Johannsen, & Rakoczy, 2019). Alternatively, the task suffered from data loss which resulted in the sample size (N = 36) to be insufficient for consistently detecting fixations in the AOIs. Eye-tracking technology is in fact known to suffer data loss for multiple reasons such as participants' eye colour, eye lashes, mascara, contact lenses (Nyström, Andersson, Holmqvist, & van de Weijer, 2013) as well as room light conditions (Zhu & Ji, 2005) and device slippage when using wearable eye-tracking-glasses (Niehorster et al., 2020). Eye blinks are another source of data loss and one that is difficult to control. During blinks the eyetracker's cameras loose the image of the pupil, resulting in missing values. Avoiding blinks all-together is not feasible and, since I did not want to interfere with participants' natural processing of the scene, they were not given the instruction to try to keep their eyes open. Then, one has to hope that blinks do not occur during the crucial time window. The fact that the frequency of their occurrence is not random, but depends on the task characteristics (Stern, Walrath, & Goldstein, 1984), such as cognitive load (Fukuda, 2001) might be part of the reason why I detected first fixations in fewer participants in Experiment 1B (42 %) compared to Experiment 1A (57 %). In fact, In Experiment 1B I introduced instructions for achieving a reward (i.e., a candy) that might have increased participants' cognitive load enough to result in high frequency of blinks during the crucial time window. As a reminder, participants in Experiment 1B knew that when the agent came back to the room she was going to either try to retrieve the candy or to open the empty box based on the colour of the cards she picked at the beginning of the experiment. Based on the box the agent tried to open and based on her true or false belief, participants had to help by opening the box matching the coloured card. For example, from a participant's point of view, if the agent knows the candy to be ultimately located in the right box (i.e., TB condition) and yet she is trying to open the empty left box, that must mean that she picked a blue card and I (participant) have to help her opening the empty box she is struggling with. The external reward was aimed at providing a normatively relevant way to perform the task and to elicit explicit false belief reasoning during the helping phase (i.e., after the eye-gaze and WBB time windows). However, participants might have devoted a significant portion of their working memory to keep track of the probability of the agent going to one box or the other based on the colour of the cards also during the crucial eye-gaze and WBB time windows. In other words, the instruction introduced in Experiment 1B might have added cognitive load to an already unusual (that is, not common in one's daily life) scenario.

Cognitive load, besides having a direct effect on eye-gaze data loss, has also been shown to affect adults' spontaneous mindreading abilities. In particular, in a study testing the influence of domain-general resources on the operation of the efficient system, Schneider, Lam, Bayliss, and Dux (2012) show that anticipatory looking in a FB task disappears under cognitive load. These results have been characterised as evidence against the automaticity (and the existence) of an efficient system for tracking belief-like states (Carruthers, 2017). Alternatively it might be that the minimal system is not only limited in the kind of information that can accommodate but also in how minimal the available cognitive resources can be before the elaboration of others' beliefs has to be taken over by a flexible and cognitively expensive system to generate accurate behavioural expectations. That is, it might be that the rule of colours introduced in Experiment 1B might have induced participants to continuously hold all the aspects involved in the scene in their working memory, which in turn resulted with the flexible system taking over the information processing while overriding the efficient system (and its associated markers such as anticipatory gazing) from the beginning .

Spontaneous motor representation of the agent's belief-based actions (as measured by means of mediolateral shifts on the WBB) might have been negatively impacted by high cognitive load as well. Although motor activation for an observed action is often described as automatic (Cracco et al., 2018) and inevitable (Iacoboni et al., 1999; Rizzolatti & Craighero, 2004), its study has been traditionally conducted using stimuli that lack in social content and that channel participants' attention towards the agent's effectors. For instance, it is common in the motor cognition field to present participants video stills of a hand performing reach-to-grasp actions while the rest of the body is out of the frame. This approach make sense when the researcher is interested in understanding whether low-level visual information is automatically converted into motor representations. Nonetheless, it is rarely (if ever) the case that in our daily life we spectate actions completely isolated from the context in which they occur. For example, if you are a first-time tourist in Times Square and you are staring at the man with the hat who is eating a cookie on the red stairs, you might be automatically representing the goal of his finely tuned movements when your attention is oriented on his body parts. However, it is NYC and sounds, lights and smells overwhelm you, all while reasoning about what museum to hit first and how unhealthy that overpriced hotdog was. Although you are still staring at the man with the hat, you might not be devolving any resource to motorically represent his actions. In fact, if the cognitive system is overloaded, for example while performing a secondary task (Chong, Cunnington, Williams, & Mattingley, 2009), or if the attention is diverted away from the agent's effectors, for example by external cues (Bach, Peatfield, & Tipper, 2007), the observed action does not trigger automatic motor representations in the onlooker at all. Conversely, looking directly at a central fixation cross while orienting the attention to a familiar action presented peripherally does activate motor processes in the observer (Puglisi, Leonetti, Cerri, & Borroni, 2018). In other words, although motor simulation in the observer can occur with relatively low cognitive demands (e.g., Cracco et al., 2018), the processing of the observed action requires some attentional resources, which can be disrupted or diverted under cognitive load or by contextual distractors in the environment.

In trying to bring together in one single experimental setting the study of mindreading and motor processes, I adapted the interactive task developed by Buttelmann et al. (2009) because it offered the untapped potential to study how participants implicitly react to an agent performing goal-directed actions with a true or false belief. Adopting a real-time scenario was effective in eliciting anticipatory gaze and mediolateral balance shifts in Experiment 1A but not in Experiment 1B. The real-time interactive nature of this study came in fact with the typical degree of variability that is difficult to control. For instance, although thoroughly rehearsed, the confederate's set of movements (as well as the experimenter's) might have been slightly different from one session to the other in a way that was not clearly evident but that was nonetheless detected by systems that can accommodate this kind of low-level information. In the same vein, the script used to create a social context that was credible to adult participants might have been too rich in content for participants to pay attention to the action. In Buttelmann et al., the experimenter hid a toy in the simple context of playing a trick to the confederate and the authors tested false belief reasoning by leveraging the tendency of children to help adults. On the contrary, adults are more sophisticated thinkers and since they are not easily deceived I had to create a story-based context that was believable enough for them to buy in the fact that the confederate was actually acting either under a true or false belief about the location of the chocolate. The social content was ultimately credible, but at the cost of making participants store in their working memory a series of unusual elements in both Experiment 1A and Experiment 1B, but with the addition of the colour-rule only in Experiment 1B. The type of context in which this kind of interaction occurs is important when trying to understand how participants process the events. For instance, it has been argued that the context of playing a trick in Buttelmann et al.' false belief condition might have put so much salience on the toy that "the trick" should be considered as a confound between false belief and true belief condition

(Allen, 2015). In my Experiment 1B, the colour-rule that was introduced to generate more credibility to the confederate's choice of box might have added cognitive load to an already unusual context. In other words, it might have been the drop that broke the camel's back, where the drop is the colour-rule and the camel's back is the cognitive capacity of the efficient system, of the motor system, or both.

The procedure adopted in Experiment 1A, and particularly in Experiment 1B, was complex. Considering the evidence suggesting that the efficient system for mindreading as well as motor processes in the observer depend, at least minimally, to cognitive resources that are difficult to control in a real-time interactive task, I decided to develop the following experiments with more tightly controlled and conventional computer-based tasks.

Chapter 5

Experiment 2

In Experiment 2, I adapted the real-time interactive task adopted in Experiment 1A and Experiment 1B into a computer-based task to measure participants' final helping behaviour as well as their fast belief-tracking and motor processes in a more controlled environment. I used the Mouse Tracker software and analyzer (Freeman & Ambady, 2009) to study the hand trajectories participants produced when helping an agent opening either a box located on the right or a box located on the left side of the screen while measuring their medioalteral leaning with a WBB. The agent had a true or false belief about the object's location and was either able to move or was motorically constrained.

The use of mouse-tracking techniques in the mindreading field is not common. However, an example of its efficacy in the study of automatic belief tracking comes from van der Wel et al. (2014). In their adaptation of the ball detection task (Kovacs et al., 2010), van der Wel and colleagues showed that analysing participants' mouse trajectories can be helpful to investigate how conflicts between one's own and others' beliefs are resolved online. In their experiment, participants watched a scene which resulted in them and the agent believing a moving ball to be ultimately located behind a left-side occluder or behind a right-side occluder. If the agent never left the room, participant and agent ended up having the same belief about the location of the ball. On the contrary, if the agent left the room before the last swap in location, participant believed the ball to be behind one occluder (e.g., left occluder) while the agent believed it to be behind the other occluder (e.g., right occluder). Participants were *not* instructed to take the agent's belief into consideration and, at the end of the sequence, they were prompted to move as quick as possible to the ball location. As soon as they moved the mouse (i.e., after a 50 pixels movement), the occluders dropped revealing the actual location of the ball. At this point, the location of the ball could be surprising for the participant, for the agent, for neither, or for both. van der Wel et al.'s (2014) results show that participants' mouse trajectories were influenced by their own as well as by the agent's belief about the location of the ball. Participants were attracted towards the unchosen alternative when they started to move the mouse towards a location that, after the occluders dropped, was revealed to be the wrong one. They did not show as much attraction when the revealed correct location was congruent with their initial movement (notice the difference between the trajectories in panel A and panel B in Figure 5.1). In addition, their attraction towards the unchosen alternative was also greater when the agent had a false belief about the location of the ball, regardless of the fact that the agent's belief was completely irrelevant for the task (e.g., compare the red line with the green line within panel A or within panel B in Figure 5.1; note that the difference between dotted and solid lines in the figure refers to an aspect not discussed here). In other words, although the agent's belief was irrelevant, participants automatically kept their own and the agent's belief in parallel when moving the mouse to click the target location.

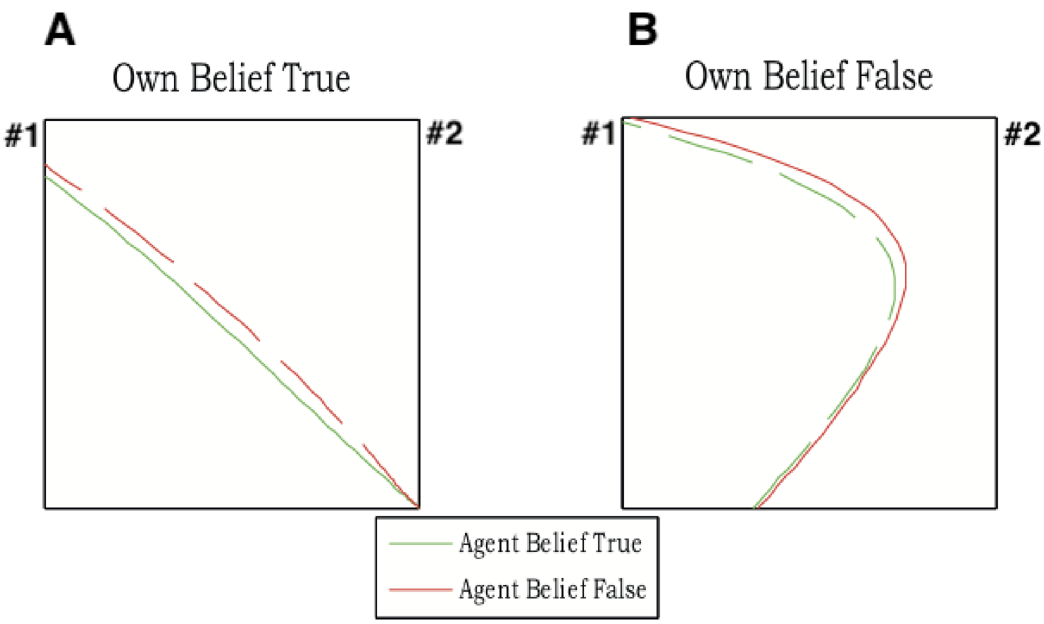


Figure 5.1: ***van der Wel, Sebanz, and Knoblich (2014)****: participants' trajectories are more attracted towards the unchosen alternative when i) they have a false belief about the location of the ball (box A versus box B) and when ii) the agent has a false belief about the location of the ball (red line versus green line). Adapted from van der Wel, Sebanz, and Knoblich (2014)*

The evidence provided by van der Wel et al. (2014) on the efficacy of using mouse tracking for studying automatic belief tracking provided empirical support to adapt the real-time interaction task that I used in

Experiment 1A and 1B to become a computer-based task. In the real-time interaction task participants helped an agent by actively reaching and opening a box on the left side of a table as opposed to a box located on the right side while their body posture was recorded by means of a WBB. In order to harvest the benefits of a multi-trial computer based task without losing the proactive characteristic, in Experiment 2, (and Experiment 3A and 3B) I preserved the natural arm extension required to perform a reach-to-touch action in real life by having participants expressing their choice by moving the mouse cursor and clicking one out of two boxes, all while the agent had a true or false belief about the object's location and was either motorically constrained or able to move.

My predictions in terms of mediolateral leaning, mouse-tracker trajectories and effect of constraint and were as follows.

In terms of adults' mediolateral balance shifts sampled at an early time point I expected to replicate the results of Experiment 1A with participants leaning towards the empty box in the FB condition and towards the full box in the TB condition.

Regarding the final choice as expressed by participants' mouse clicks, since there is no normatively correct helping response to the helping task (Fizke et al., 2017), as indicated by failures to conceptually replicate the original findings of Buttelmann et al. (2009) with adults, in Experiment 1A and Experiment 1B, as well as with children (Crivello & Poulin-Dubois, 2018; Priewasser et al., 2018), all the responses were recorded and coded as correct.

If participants automatically track the agent's belief, I expected that in False Belief condition their mouse trajectories landing on the full box should be pulled towards the empty box (i.e., the box in which the agent falsely believes the object is located and that the agent tried to open at the end of the sequence of events) while participants' mouse trajectories landing on the empty box should not be pulled towards the full box (i.e., the box that the agent falsely believes to be empty). In True Belief condition, their trajectories aiming at the empty box should be pulled towards the full box (i.e., the box in which the agent truly believes the object is located although she did not try to open) while participants' trajectories aiming at the full box should not be pulled towards the empty box (i.e., the box in which the agent truly believes the object is not located although the agent tried to open).

Finally, I predicted that any indication of fast belief tracking abilities detected in participants' body posture and mouse cursor trajectories might be disrupted by impairing participants' ability to motorically represent the agent's goal.

5.1 Mouse Tracker

As of today, reaction time (RT) is the most commonly used technique to investigate psychological processes that occur in the hundred of milliseconds. RTs have helped in better understanding the cognitive processes underlying decision in multiple choice tasks, and still are the golden standard in mental chronometry. However, mouse tracking is also well-suited to study online decision processes. Mouse tracking can provide insights on the spatiotemporal dynamics of dual-system processes by analizing probabilistic mid-flight corrections (e.g., an initial fast and automatic hand movement towards a cupcake followed by a high-level and cognitively effortful correction toward the healthier banana) (Freeman, 2018), and its measures (e.g., Maximum Deviation) provide stronger activation in those brain areas associated with conflict-monitoring compared to activation produced when measuring RTs (Stolier & Freeman, 2017).

Typically, in a mouse-tracker experiment, participants begin a trial by clicking a box located in the bottom centre of the screen and then they move the mouse cursor to one of two alternatives in the top corners of the screen. The resulting trajectory is recorded at a high temporal resolution of 60-75Hz (Freeman & Ambady, 2010) and provides information about the attraction that the unchosen alternative has on the participant. Such mouse trajectory attraction is commonly operationalised in terms of Maximum Deviation (MD, greatest distance between the observed trajectory and the ideal straight trajectory that connects the starting location with the chosen location) or Area Under the Curve (AUC, the geometrical area between the ideal trajectory and the participant's trajectory) (see Figure 5.2). The AUC is calculated by summing any curvature heading towards the unchosen alternative (computed as positive AUC) and any curvature heading away from the unchosen alternative (computed as negative AUC) (Freeman & Dale, 2013; Xiao & Yamauchi, 2017). For example, when participants are asked to categorise a face as belonging to a male or female, the AUC of their mouse trajectories is greater when they are shown a picture of a male with feminine features (e.g. long hair) compared to when they are presented with a picture of a male with typical male features (Freeman, Ambady, Rule, & Johnson, 2008).

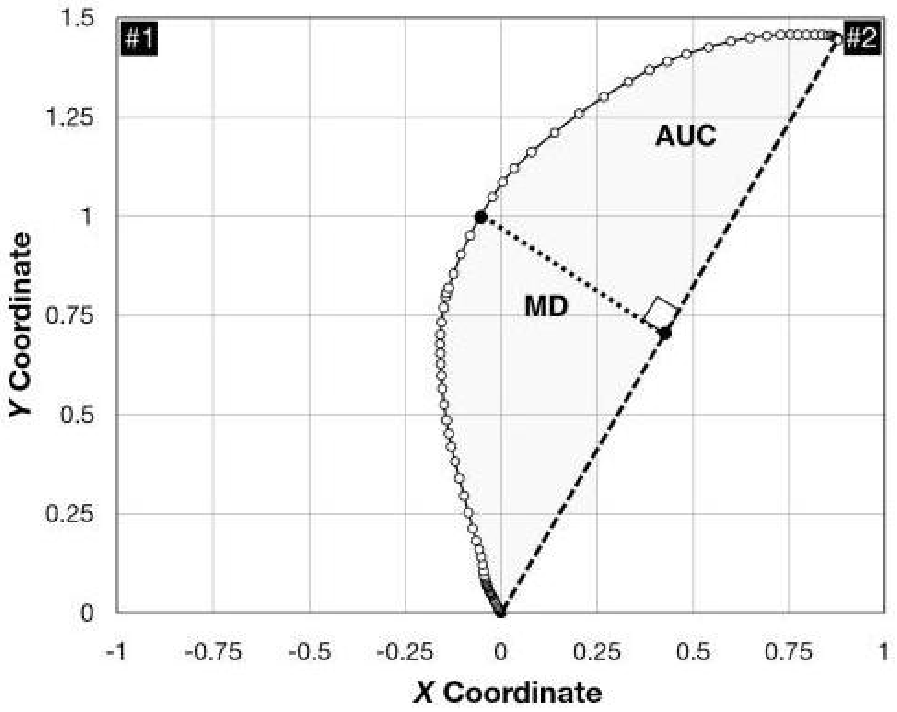


Figure 5.2: ***Area Under the Curve and Maximum Deviation****: example of spatial attraction toward an unselected alternative. The Area Under the Curve (AUC) is the area between the ideal straight line connecting the starting location with the target location and the observed trajectory. The Maximum Deviation (MD) is the maximum distance registered between the ideal straight line and the observed mouse cursor trajectory.*

5.2 Method

5.2.1 Participants

I ensured that the sample size was adequate to have a power of at least .90 as highlighted in section 4.1.2.1 (31 participants) and to accommodate for the average exclusion rate detected in Experiment 1A (16%) and Experiment 1B (7%) [(.16+.07)/2 x 31 = 3.6 additional participants for a total of at least 35 participants)]. Fifty-nine right-handed adults (M = 19.4 years, range = 18 to 31 years, 34 females and 25 males) were included for this experiment.

5.2.2 Stimuli and Procedure

Participants were tested individually in a single experimental session lasting approximately 1 hour. They were asked to stand on a Wii balance board with the right hand holding a mouse and the left hand comfortably resting on the table. They were instructed to watch the video clips that were presented on a monitor in front of them and to unlock one of the two boxes by clicking on it every time that the agent asked for help. Participants watched 18 videos per condition, for a total of 72 trials. The order of the videos and the initial location of the chocolate was randomised across participants.

4 video clips were adopted as experimental stimuli (see Figure 5.3 on page 155 for a schematic representation of their time sequence):

a) **True Belief Untied** (TBU): after the agent placed a chocolate bar in one of the two boxes, the experimenter (watched by the agent) moved the chocolate bar from that box to the other box. Then the agent left the room. While the agent was outside the room, the experimenter locked the boxes with a black pin. Note that the locking mechanism was seen from the participant's point of view but not by the agent. Then the agent came back into the room and, after 1200 ms, she reached for the empty box. After unsuccessfully trying to open the lid, the agent assumed a neutral position and the sentence prompt "help me" appeared on the screen.

b) **False Belief Untied** (FBU): after placing a chocolate bar in one of the two boxes, the agent left the room. While the agent was outside, the experimenter moved the chocolate bar from one box to the other and he locked the boxes with a black pin. Note that the locking mechanism was seen from the participant's point of view but not by the agent. Then the agent came back into the room and, after 1200 ms, she reached for the empty box. After unsuccessfully trying to open the lid, the agent assumed a neutral position and the prompt "help me" appears on the screen.

c) **True Belief Tied** (TBT): after the agent placed a chocolate bar in one of the two boxes, the experimenter (watched by the agent) moved the chocolate bar from that box to the other. Then the agent left the room. While the agent was outside the room, the experimenter locked the boxes with a black pin. The locking mechanism was seen from the participant's point of view but not by the agent. When the agent came back into the room it was clearly shown that her ability to move was impaired by bandages blocking her arms and legs (the agent's tunic was warn as movement-restricting bandages). After 1200ms the agent leaned towards the the empty box. Then the agent assumed a neutral position and the promt “help me” appeared on the screen.

d) **False Belief Tied** (FBT): after placing a chocolate bar in one of the two boxes, the agent left the room. While the agent was outside, the experimenter moved the chocolate bar from one box to the other and he locked the boxes with a black pin. The locking mechanism was seen from the participant’s point of view but not by the agent. Then the agent came back into the room and it was clearly shown that her ability to move was impaired by bandages blocking her arms and legs. After 1200 ms the agent leaned towards the empty box. Then the agent assumed a neutral position and the prompt “help me” appeared on the screen.

Participants’ leaning on the WBB was recorded during a time window with a fixed duration of 1200 ms starting when the agent came back into the room and ending before the agent leaned towards one of the boxes. The mouse tracker time window had a maximum duration of 3000 ms and started when the prompt ”help me” appeared on screen and ended when the participant clicked on one of the two alternatives (see Figure 5.3). If participants took $\geq$ 400 ms to move their mouse, after their choice, a message appeared on screen prompting a faster response in the following trials (i.e., ”Please start moving earlier on, even if you are not fully certain of a response yet”).

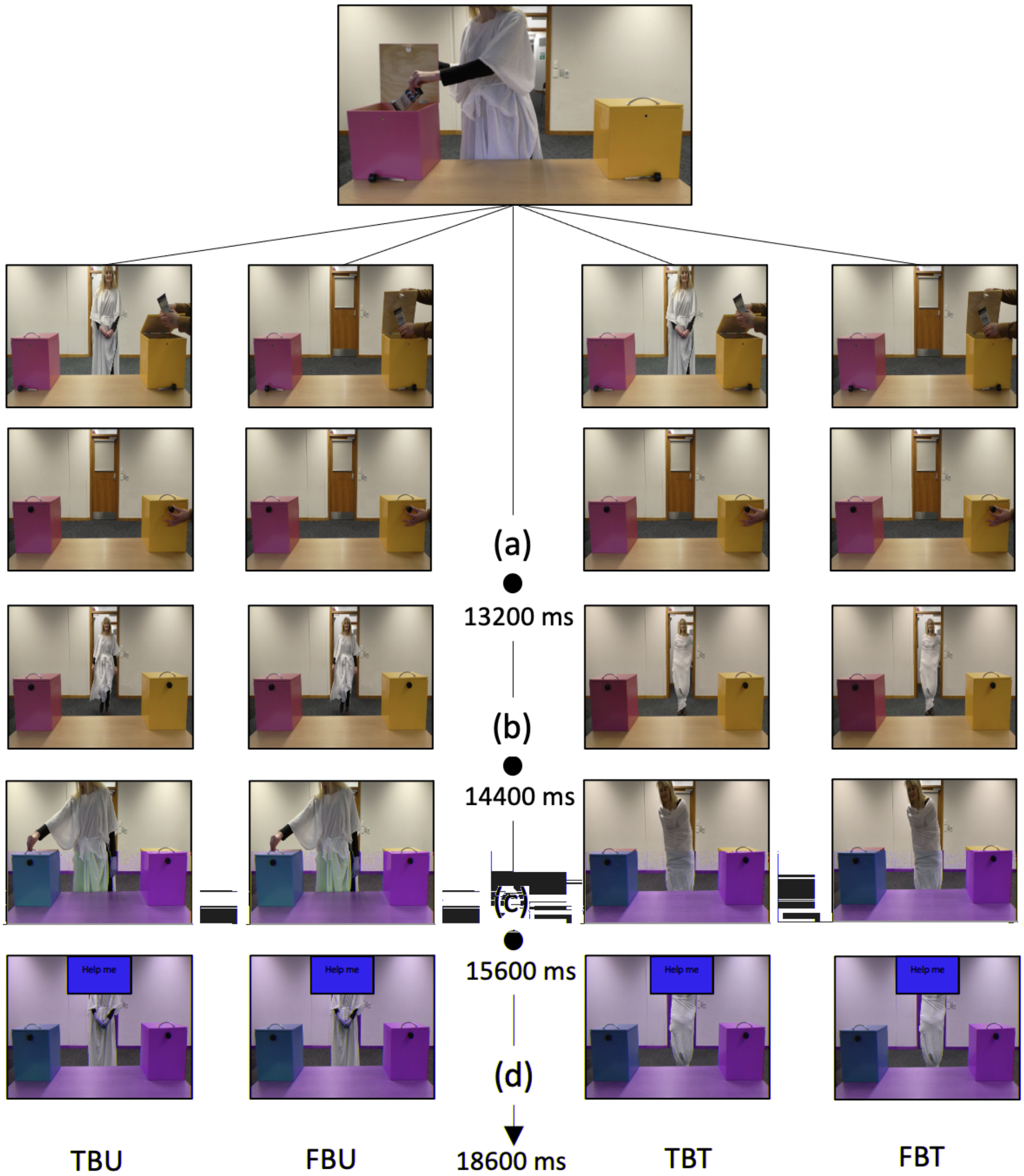


Figure 5.3: ***Experiment 2: Times of Interest.*** *The balance time window had a fixed duration of 1200 ms starting when the agent came back into the room (a) and ending before the agent leaned towards one box (b). The mouse tracker time window had a maximum duration of 3000 ms and started when the prompt "help me" appeared on screen (c) and ended when the participant clicked on one of the two alternatives (d).*

5.2.3 Results

5.2.3.1 Balance analysis

I analysed participants' mediolateral leaning on the WBB (N = 46/59); balance board data of two participants were not acquired due to technical problems. Furthermore, given the multi-trial nature of Experiment 2, some of the participants found it difficult remain still and relaxed for the whole duration of the experiment. For this reason, I visually inspected the raw WBB data to check for participants' ability to consistently hold a relaxed and stable body posture. Following the approach used by Zwaan et al. (2012), participants (eleven) with a Center of Pressure (COP) exceeding $\pm$ 4 cm before or during the critical time-window were excluded (see Figure 5.4 for an example of the distribution of body displacement in one included participant versus one excluded participant). Mann–Whitney U-tests were conducted to determine whether there was a difference in the average leaning between conditions.

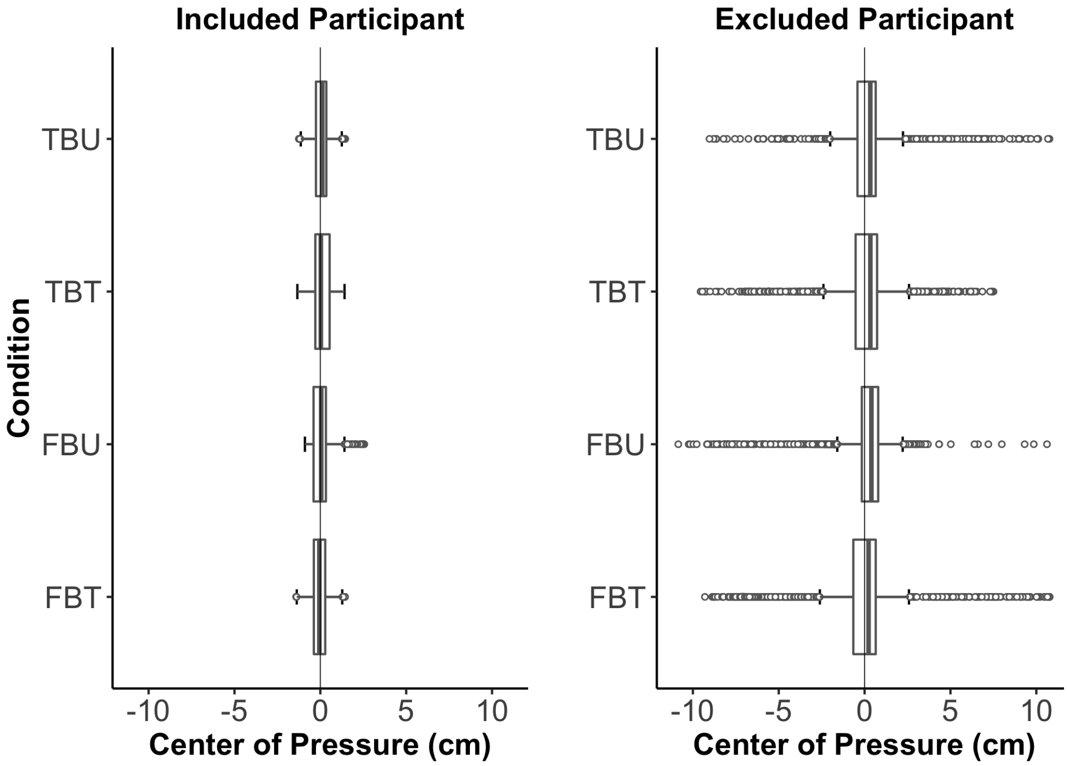


Figure 5.4: ***Experiment 2: Example of displacement from body midline of one included participant compared to one excluded participant.*** *Positive values reflect rightward body shifts; negative values reflect leftward body shifts. Continuous line in the box represents the median, length of the box represents the interquartile range and the whiskers extend to the highest and lowest observations. Points outside the box are outliers (quartile $\pm$ 1.5 times the IQR).*

Replicating Experiment 1A, results revealed a significant difference between TBU and FBU conditions (Mann-Whitney U = 748, p = 0.015; Figure 5.5), with participants in the FBU condition leaning towards the now-empty box (M = -0.007, s.d. = 0.03, CI = -0.015, 0.003) and participants in the TBU condition leaning towards the now-full box (M =

0.007, s.d. = 0.026, CI = -0.001, 0.014). Non-significant differences emerged from the remaining Mann-Whitney *U* tests conducted between conditions: TBU-TBT (Mann-Whitney $U = 846$, $p = 0.098$) with leaning in the TBT condition not attenuated at a significant level ($M = 0.002$, s.d. = 0.04, CI = -0.01, 0.014); FBU-FBT (Mann-Whitney $U = 968$, $p = 0.482$) with leaning in the FBT condition not attenuated at a significant level ($M = -0.003$, s.d. = 0.031, CI = -0.012, 0.006); TBT-FBT (Mann-Whitney $U = 1053$, $p = 0.969$) with participants' body posture almost overlapping across Tied conditions.

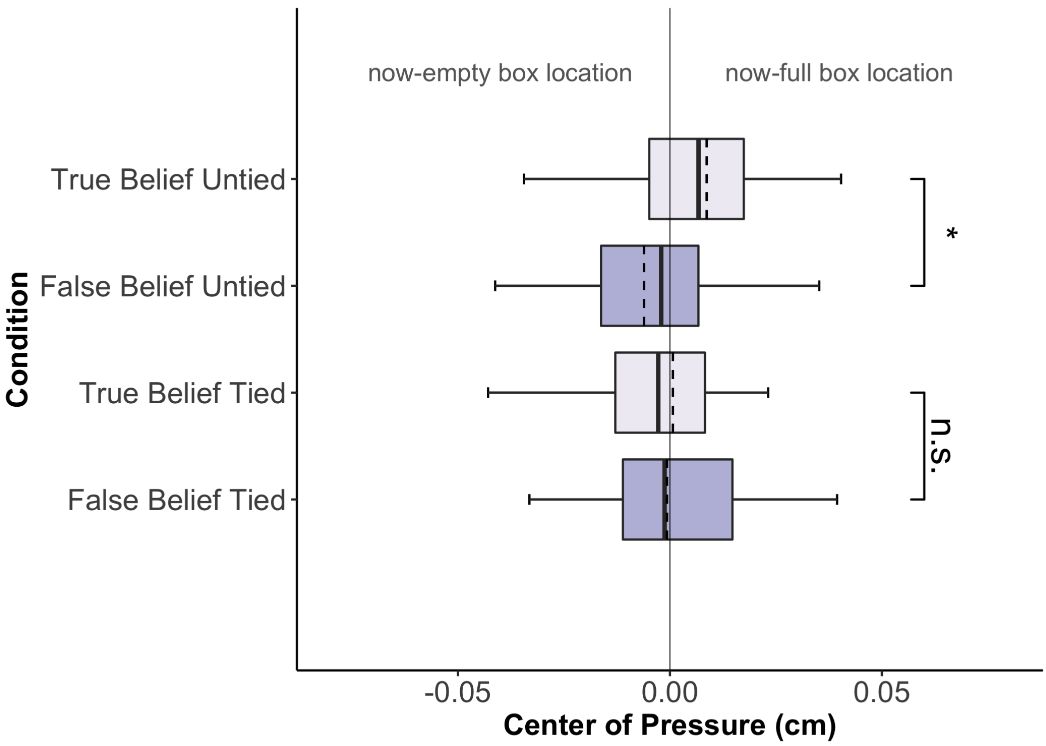


Figure 5.5: ***Experiment 2: displacement from body midline.*** *Displacement from body midline (0) between groups (True Belief Untied, False Belief Untied, True Belief Tied, False Belief Tied). Positive values reflect a leaning towards the now-full box; negative values reflect a leaning towards the now-empty box. Dotted line in the box represents the mean, continuous line represents the median, length of the box represents the interquartile range and the whiskers extend to the highest and lowest observations.*

5.2.3.2 Mouse Tracker analysis

Implementing the Mouse Tracker in Experiment 2 allowed me to record participant's final helping behaviour as a binary outcome (i.e., participants either clicked on the now-full box or the now-empty box) while analysing their mouse cursor trajectories to investigate how conflicts between one's own and others' beliefs are resolved online. The responses were recorded with a Logitech G502 mouse (set at 1000 DPI and 125 Hz). The mouse-tracking software response boxes were over-imposed on the the unlocking mechanisms, which were 56 pixels in height and width and were located approximately on the midline of the screen (i.e., 600 pixels upwards and 1690 pixels sideway). In the current literature, there is only one Mouse Tracker experiment aimed at investigating the effects of an agent's belief on participants' mouse trajectories (van der Wel et al., 2014). In particular, in their ball detection task, van der Wel et al. asked their participants to provide their response by clicking on the location of a ball and coded as correct only those mouse trajectories ultimately landing on the ball. This allowed the authors to analyse trajectories with an a priori specified goal (i.e., "click the ball") and compare the influence of one own and another person's beliefs on the mouse trajectory (by means of their Area Under the Curve; AUC). Like van der Wel et al., I also analysed participants' AUC, but my approach to the data was slightly different. In fact, since there is no normatively correct helping response to the helping task (Fizke et al., 2017), as indicated by failures to conceptually replicate the original findings of Buttelmann et al. (2009) with adults, in Experiment 1A and Experiment 1B, as well as with children (Crivello & Poulin-Dubois, 2018; Priewasser et al., 2018), all the responses were recorded and coded as correct.

In the following data analysis, I explored the amount of attraction exerted by the non-chosen alternative on the trajectories of the mouse cursor, as expressed by the Area Under the Curve (AUC) of each trajectory (see Section 5.1 for a detailed description of Mouse Tracker analysis).

Before performing formal analysis, I excluded from the dataset all trials (4.45%) in which the initiation time (*IT*, amount of time that the mouse cursor takes to reach a distance of 30 px from the centre of the starting location) was greater than 400 ms. Having an *IT* set at 400 ms is not necessary when running a Mouse Tracker experiment, and some researchers avoid using it altogether (e.g., Kieslich & Hilbig, 2014; Koop & Johnson, 2013), nonetheless it has been described as the optimal cutoff to be adopted when measuring online processes in Mouse Tracker experiments (e.g., Freeman & Ambady, 2009; Hehman, Stolier, & Freeman, 2015). Since all participants had an *IT* below 400 ms in more than 75% of the trials across and within conditions, they were all included in the final analysis.

After checking the raw data for $IT \geq 400$ ms, as per standard practice in mouse-tracker experiments (e.g., Freeman & Ambady, 2010; Koop & Johnson, 2011; Spivey, Grosjean, & Knoblich, 2005), I remapped all trajectories to one side of the screen and, because raw trajectories varies in duration (and thus they contain a different number of data points), I normalized them into 101 time steps using the linear interpolation provided in the the Mouse Tracker Analyser software (Freeman & Ambady, 2009). Combined, these two transformations facilitate meaningful comparisons. Lastly, I excluded trials in which the Area Under the Curve (AUC) was deviating more than 2 standard deviations from the average.

Since several participants did not choose to click the now-full box and the now-empty box at least once per condition (e.g., multiple participants never clicked the now-empty box in the False Belief Untied condition), I analysed MT data in a linear-mixed model using participants as random intercept and final choice (now-empty; now-full), condition (True Belief; False Belief), constrain (Untied; Tied) and their interaction as predictors [similar to the approach adopted by Kieslich and Hilbig (2014)]. Table 5.1 provides the descriptive statistics about the number of times (i.e., ”Count”) that participants chose to help by clicking on one box (e.g., now-empty; ne-) or the other (e.g., now-full; nf-) in each condition.

Table 5.1: *Experiment 2: mean Areas Under the Curve (AUC) by chosen box in each condition (neTBU, now-empty box in True Belief Untied; nfTBU, now-full box in True Belief Untied; neFBU, now-empty box in Frue Belief Untied; nfFBU, now-full box in False Belief Untied; neTBT, now-empty box in True Belief Tied; nfTBT, now-full box in True Belief Tied; neFBT, now-empty box in False Belief Tied; nfFBT, now-full box in False Belief Tied).*

	Count	Mean AUC	sd
neTBU	348	−0.066	0.343
nfTBU	606	−0.019	0.356
neFBU	27	0.016	0.219
nfFBU	785	−0.001	0.167
neTBT	359	−0.007	0.274
nfTBT	596	−0.005	0.154
neFBT	190	−0.019	0.254
nfFBT	768	−0.010	0.227

No significant main effects nor interactions emerged. No main effect of choice ($F_{(1, 332.63)} = 0.518$, $p = .472$), condition ($F_{(1, 324.22)} = 0.855$, $p = .356$) nor constraint ($F_{(1, 324.42)} = 0.168$, $p = .682$); no interaction between condition and choice ($F_{(1, 323.27)} = 0.968$, $p = .326$), between condition and constraint ($F_{(1, 323.28)} = 2.592$, $p = .108$), between choice and constraint ($F_{(1, 323.63)} = 0.04$, $p = .842$) nor between condition, choice and constrain ($F_{(1, 324.336)} = 0.878$, $p = .350$).

In general, regardless of the condition, participants' trajectories were not attracted towards the unchosen alternative, as indicated by negative AUC values. Recall that the AUC is the geometrical area between the ideal straight trajectory and the participant's trajectory, it is calculated by summing any curvature heading towards the unchosen alternative (computed as positive AUC) and any curvature heading away from the unchosen alternative (computed as negative AUC) (Freeman & Dale, 2013; Xiao & Yamauchi, 2017). That is, any AUC exceeding the ideal path towards the chosen alternative is subtracted from the AUC value. By looking at the mouse trajectories, it is in fact evident that participants, after a brief upward movement, moved the mouse sharply towards the chosen alternative (see Figure 5.6).

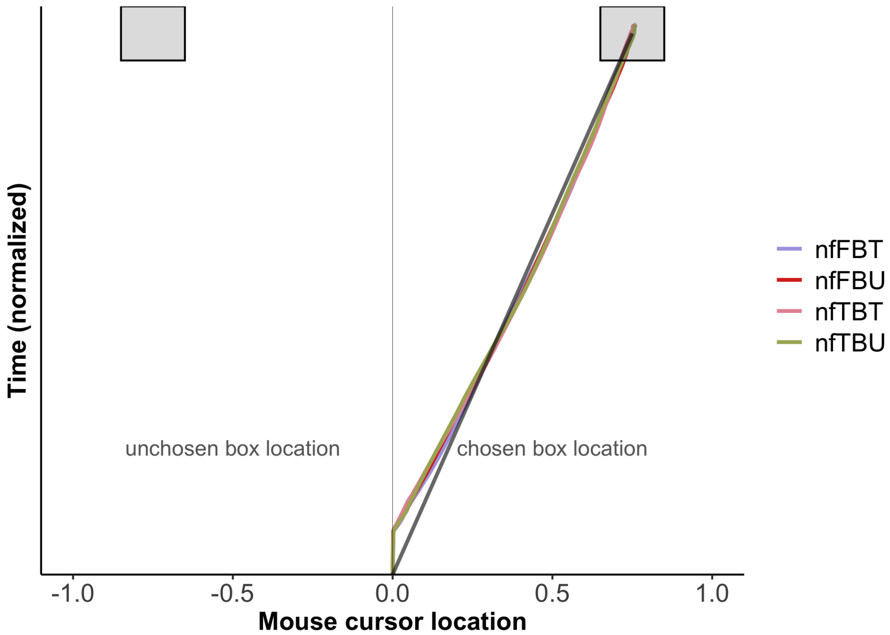


Figure 5.6: ***Experiment 2: averaged mouse cursor trajectories.*** *Examples of averaged mouse cursor trajectories directed at the now full box (i.e., nf-) to show that the AUC was negative because the curvature heading towards the chosen alternative (computed as negative AUC) is stronger than the curvature towards the the unchosen alternative (computed as positive AUC). The straight thick line represent the ideal path connecting the starting location with the chosen box.*

5.2.3.3 Final Helping behaviour analysis

Since the final helping behaviour had a binary outcome (i.e., participants had to help the agent by opening either the now-full box or the now-empty box) that was recorded in multiple trials, differently from Experiment 1A and Experiment 1B, it was necessary to calculate the final helping behaviour proportions. The final helping behaviour proportion was defined as the number of choices to help with the now-full box in a specific condition (e.g., TBU) divided by the total number of the trials in that condition. As the proportions were not normally distributed, I performed all the analysis with non-parametric tests (Wilcoxon Signed Rank Tests).

The results showed that participants chose to help with the now-full box significantly more in the FBU condition compared to the TBU condition (Z = -4.134, $p<0.001$), more in the FBT condition compared to the TBT condition (Z = -3.104, p = 0.002) and more in the FBU condition compared to the FBT condition (Z = -4.336, $p<0.001$). No difference in helping behaviour was detected between TBU and TBT conditions (Z = -0.016, p = 0.987) (see Table 5.2).

Table 5.2: *Experiment 2: descriptive statistics of the proportions of Final Helping Behaviour with now-full box as outcome by condition (TBU, True Belief Untied; FBU, False Belief Untied; TBT, True Belief Tied; FBT, False Belief Tied).*

	Mean	Median	std. dev.
TBU	0.63	0.83	0.4
FBU	0.97	1	0.06
TBT	0.63	0.78	0.38
FBT	0.8	0.94	0.31

5.2.4 Discussion

First, in line with the results obtained in Experiment 1A, the analysis of adults' mediolateral balance shifts confirmed spontaneous motor anticipation of belief-based actions in FBU and TBU conditions. In the FBU condition, adults leaned towards the empty box i.e. the box in which the agent believed the object to be located; in the TBU condition, they leaned towards the full box i.e. the box in which the agent knew the object was located. The fact that the mediolateral difference between true belief condition and false belief condition disappears when manipulating the agent's ability to move (i.e., TBT = FBT) is suggestive of an attenuation of participants' ability to motorically represent the goal of the observed action. However, the lack of a significant effect within conditions (i.e., TBU = TBT; FBU = FBT) also indicates that the effect of constraint on the ability to generate motor predictions about observed belief based actions is not conclusive. One potential explanation for why anticipatory mediolateral leaning was not completely obliterated by motor restrictions is that constraining the agent might not be as effective in disrupting motor processes in the observer as directly interfering with participants' ability to move (Ambrosini et al., 2012) or as disrupting their motor-related cortical areas (Costantini et al., 2014). However, impairing an agent's ability to move has been shown to be effective in disrupting motor preparation (Liepelt et al., 2009) as well as fast-belief tracking (Low et al., 2020; Sinigaglia et al., 2021) in the observer. It may be that the effect of motor restriction in Experiment 2 was not as strong because the constrained agent was consistently ending the sequence by leaning towards one box before the prompt ”help me” appeared on screen. Although the leaning motion occurred after the WBB time window, participants’ motor system might have used this information to generate expectations about which location the constrained agent was going to lean towards in the upcoming trials. Alternatively, the motor system might not be necessary for fast action prediction, as indicated by evidence showing that participants born without upper limbs are able to generate behavioural expectations (Vannuscorps & Caramazza, 2016). Overall, more research is needed to clarify the boundaries and limits of spontaneous action prediction.

Second, participants’ mouse cursor trajectories were not attracted towards the unchosen alternative, as indicated by negative AUC values. The lack of attraction towards the box in which the agent believed the chocolate to be located is different from the effect observed by van der Wel et al. (2014). In their ball detection task, van der Well and colleagues found that participants clicked the location of the ball with trajectories that were influenced by the agent’s belief about the location of the ball. It is possible that the apparent lack of attraction towards the unchosen alternative might be originated from a possible confound that was introduced in the design phase. In fact, in my attempt to maintain as much as possible some of the ecological validity of Experiment 1A and Experiment 1B, I had participants click response boxes that were over-imposed i.e. camouflaged onto the unlocking mechanism. The unlocking mechanisms and relative response boxes were located approximately on the midline of the screen (i.e., 600 pixels upwards and 1690 pixels sideway). The fact that the response boxes were not located in the top right and top left corners, as it is commonly done in mouse tracker experiments (e.g., Freeman, 2018; van der Wel et al., 2014) might have forced participants in Experiment 2 to exert a strong and early correction towards the chosen alternative, ultimately resulting in their trajectories not having the time and space to be pulled towards the opposite location (see Figure 5.7 for a simplified representation of the location of the response boxes in Experiment 2 compared to the the location in a typical Mouse Tracker task).

Figure 5.7: ***Experiment 2: location of the response boxes in Experiment 2*** *simplified comparison of the placement of the response boxes in (a) the top right and top left corners in traditional Mouse Tracker experiments compared to (b) the middle section of the screen in Experiment 2 (the actual response boxes were camouflaged)*

Lastly, considering that there is no normatively correct helping response to the helping task (Fizke et al., 2017), as indicated by failures to conceptually replicate the original findings with adults, in Experiment 1A and Experiment 1B, as well as with children (Crivello & Poulin-Dubois, 2018; Priewasser et al., 2018), I did not make any specific prediction on participants' final helping behaviour. Nonetheless, adults surprisingly showed a pattern of explicit behaviour that could be interpreted as similar to the original Buttelmann et al.'s (2009) findings. As a reminder, infants in Buttelmann et al.'s task helped by opening the now-full box in the FB condition and the now-empty box in the TB condition. Although participants in Experiment 2 chose to help by clicking the now-full box more than the now-empty box in all the conditions (see Table 5.2), they did so more in FBU compared to the TBU as well as more in the FBT compared to the TBT. One possibility, as per Buttelmann and colleagues explanation, is that participants helped in retrieving the object more in the FB conditions because they understood that the agent was trying to retrieve the chocolate where she last saw it, so they helped her in getting the chocolate. In the same vein, they opened the empty box more in the TB condition because they reasoned that since the agent knew where the object was she must have had another reason to try to open the empty box. Alternatively, it might be that secretly hiding the chocolate in the FB condition made it more salient so to generate the expectation that the agent was going to look for it (Allen, 2015), or that the fact that the agent did not complain about an unrequested change of location in the TB condition might have signalled that the agent was not the owner of that chocolate (Priewasser et al., 2018). Considering that closer replications with adults (Experiment 1A and Experiment 1B) of the original helping task did not reproduce Buttelmann et al.'s results, I maintain that there is not a normatively correct way to perform a helping behaviour in a

Buttelman helping task (Fizke et al., 2017).

In conclusion, Experiment 2 replicated Experiment 1A's results in terms of mediolateral leaning in anticipation of an agent's belief-based action. However, bodily constraining the agent was not as effective in disrupting participants' motor processes as it has been reported in recent studies (Low et al., 2020; Sinigaglia et al., 2021). Further, unlike van der Wel et al. (2014), the analysis of participants' mouse trajectories did not reveal conflicts between one's own and others' beliefs. Finally, although in Experiment 2 adults clicked more the full box than the empty box in all conditions, their helping behaviour was consistent with the results found by Buttelmann et al. (2009) with infants.

I originally adopted Buttelmann's real-time interaction task for Experiment 1A and Experiment 1B because it offered the untapped potential for documenting adults' spontaneous motor processing in the anticipation of others' belief-based actions. Its adaptation into a computer-based task was successful in eliciting participant's anticipation of belief-based actions when the agent was free to move but it also carried over two possible confounds that will be addressed in Experiment 3. First, in order to retain the aspect of an agent who wants to open a particular box, the constrained agent (i.e., TBT; FBT) leaned towards a box after the WBB time window and before asking for help. Since I was aiming to interfere with adult observers' motor processes by disrupting the agent ability to move, the fact that the agent was actually proven to be able to lean might have partially hindered the manipulation that I was aiming for. Second, the helping behaviour is traditionally carried out by directly interacting with the box participants want to help with. For this reason, I camouflaged the mouse-tracker response boxes over the actual boxes' unlocking mechanisms and I instructed participants to help by clicking one of the the two black pins that were locking the lids. Having participants interacting with the experimental boxes was indeed the most natural adaptation of the action executed by infants (Buttelmann et al., 2009) as well by adults (Experiment 1A and Experiment 1B) in the real-time versions of the task. However, the mid-screen location of the boxes might have not allowed for the mouse trajectories to develop in time and space as in traditional mouse-tracking experiments, whereby the response boxes are located in the top corners of the screen.

In Experiment 3, the task will be simplified and the helping component dropped to account for the possible confounds and to further refine an appropriate methodology for studying the relationship between implicit motor and mindreading processes.

Chapter 6

Experiment 3

The results of Experiment 1A and Experiment 2 suggest that automatic belief tracking abilities are functionally related to motor processes, as indicated by adults leaning towards the empty box in the FB condition and towards the full box in the TB condition. Adjustments in adult observers' own mediolateral leaning occurred before the agent performed any overt reaching movement towards a particular box location, as if observers' motor activity anticipated the likely target of the agent's upcoming belief-based action. However, contrary to recent evidence showing that bodily constraining an agent disrupts participants' belief-tracking abilities (Low et al., 2020; Sinigaglia et al., 2021), manipulating the agent's ability to move in Experiment 2 was not as effective. Participants' implicit mediolateral leaning in anticipation of the agent's action was disrupted during the observation of a constrained agent, as indicated by their balance being no longer directed at the full box in the TB condition and at the empty box in the FB condition. Nonetheless, the motor restriction was not completely effective in zeroing anticipatory leaning, as suggested by participant's body posture being not significantly different between TBU and TBT and between FBU and FBT. Our prediction that the disruption of belief tracking abilities might follow the disruption of motor processes needs further investigation.

Further, by measuring continuous hand movement trajectories, previous research has shown that in a False Belief task one own's beliefs about the location of an object are automatically influenced by another person's irrelevant beliefs (van der Wel et al., 2014). In Experiment 2, we investigated participant's online decision processing by measuring their mouse cursor trajectories in a computerised version of the standard Buttelman's helping task. Based on van der Wel et al.'s results, we predicted that participants' hand trajectories during the execution of helping behaviour would have been influenced by another person's beliefs about the location of an object. And, since constraining an agent's opportunity to act disrupts motor representations about others' actions (Costantini et al., 2014; Liepelt et al., 2009), we also predicted that disrupting participants' ability to motorically represent the goals of the observed action, would have also disrupted the influence of an agent's belief on participants' hand trajectories. Neither of these mouse-tracking predictions were supported in Experiment 2.

Experiments 1A, Experiment 1B and Experiment 2 highlighted a puzzling pattern of adults' final helping behaviour which is not consistently in line with the results found by Buttelmann et al. (2009) with infants. Using a real-time interaction task in Experiment 1A and Experiment 1B elicited final helping responses that were directed at the box the agent was directly struggling with (i.e., empty box). On the contrary, participants in the computer-based task used for Experiment 2 chose to help by clicking the full box more than the empty box in all the conditions (see Table 5.2), but they did so more in FBU compared to the TBU as well as more in the FBT compared to the TBT. The pattern of helping behaviour observed in my experiments is in line with the view that there is not a normatively correct way for adults (Experiment 1A, Experiment 1B and Experiment 2) to perform a helping behaviour in a Buttelmann helping task, as also indicated by failures to replicate the original results with infants and young children (Crivello & Poulin-Dubois, 2018; Priewasser et al., 2018).

The helping task was not adopted in my experimental work to assess its validity in the study of belief reasoning but it was rather used as a tool to investigate the functional relationship belief-tracking and motor processes. Considering the design limitations of using a computerised version of the helping task to study fast mindreading and motor processes, as discussed in Experiment 2, in Experiment 3A and Experiment 3B participants were not given the possibility to help the agent with either the now-empty box or the now-full box. Instead, they were instructed to click on the final location of the chocolate. In particular, removing the helping component conferred three advantages. First, not having the agent leaning towards one box before asking for help removes the possible motoric confound of a constrained agent that has some degree of freedom to move. Second, asking participants to indicate the location of the chocolate allowed the use of response boxes that could have a standard size and location as found in literature (e.g., Freeman, 2018; van der Wel et al., 2014) as opposed to using the more ecologically valid (but small and awkward in location) camouflaged response boxes. Third, having correct-incorrect responses (as per van der Wel et al.) allowed to isolate the effect of the agent's irrelevant beliefs and ability to move on mouse cursor trajectories landing on the actual location of the chocolate. Experiment 3A and Experiment 3B were designed to test if adults' automatic belief tracking abilities (as revealed by their mouse cursor trajectories) are modulated when the agent is physically constrained as opposed to when she is able to move (with Experiment 3B using a manipulation to ensure that participants visually perceived the agent).

6.1 Experiment 3A

First, I tried to conceptually replicate the effect of an agent's irrelevant belief about the location of an object on participants mouse cursor trajectories, as found by van der Wel et al. (2014). Second, I predicted that bodily constraining the agent would disrupt the influence of the agent's belief on participant's hand movements. It is worth noting that the data collection was performed during a period in which Covid-19 rules in New Zealand imposed restrictions on the recruitment of participants. Due to the uncertainty of how long the period of grace could last, Experiment 3A (as well as Experiment 3B) was designed as a computer-based task that could be run on multiple computers (i.e., fourteen) at the same time to allow fast data collection. Unfortunately, the multi-participants nature of the studies and the lack of enough physical balance boards did not allow for WBB data collection.

6.1.1 Method

6.1.1.1 Participants

The effect size in the mouse-tracking task adopted by van der Wel et al. (2014) ($F_{1,39}$ = 4.36, $p < 0.05$), η^2 = 0.1) was medium to large at f = 0.33 (the square root of eta square divided by 1 minus eta square). G*Power 3.1 indicated that a sample size of 35 would be needed to reach the desired power of .80 for the van der Wel et al. style of data characteristics (input: f (U) = 0.33, error probability = .05; number of groups = 1, number of measurements = 4). Fifty-one right-handed adults (M = 20.2 years, range = 17 to 36 years, 43 females and 8 males) were recruited for this experiment and they were all included in the final data analysis.

6.1.1.2 Stimuli and Procedure

Participants were tested in groups of 14 in a single experimental session lasting 20 minutes. Each participant was assigned to a computer with a blank screen and a start button already set up to initialise the experiment after receiving the instructions. The instructions were provided simultaneously to all participants as follows. While a video still representing the agent standing between two boxes and holding a chocolate bar was projected on a big screen, the experimenter read out loud the attached caption. "This is a computer-task that takes about 10 to 15 minutes. For every trial you will see a scene showing 2 boxes and a person inside a room, and also there is a single chocolate bar being moved from one box to another box. You have to observe what happens. After you hear a beep sound, the person comes back into the room and you have to click on a button as quickly as possible to indicate whether the chocolate bar is in the Right box or the Left box. Let me show you what a trial looks like. After signing the consent form, put your headphones on and click OK to start the computer-task." At this point, a True Belief example trial was played for everyone to see, then participants could begin the experiment.

4 video clips were adopted as experimental stimuli (see Figure 6.1 for a schematic of the crucial events as they occurred in each condition). The videos were presented in 8 blocks of 4 videos each, for a total of 32 trials. The order of the videos and the location of the chocolate was randomized across participants. If participants took $\geq$ 400 ms to move their mouse, after their choice, a message appeared on screen prompting a faster response in the following trials (i.e., "Please start moving earlier on, even if you are not fully certain of a response yet"). Further, if participants clicked on the wrong location (i.e., the empty box), the message "Wrong location" appeared on screen.

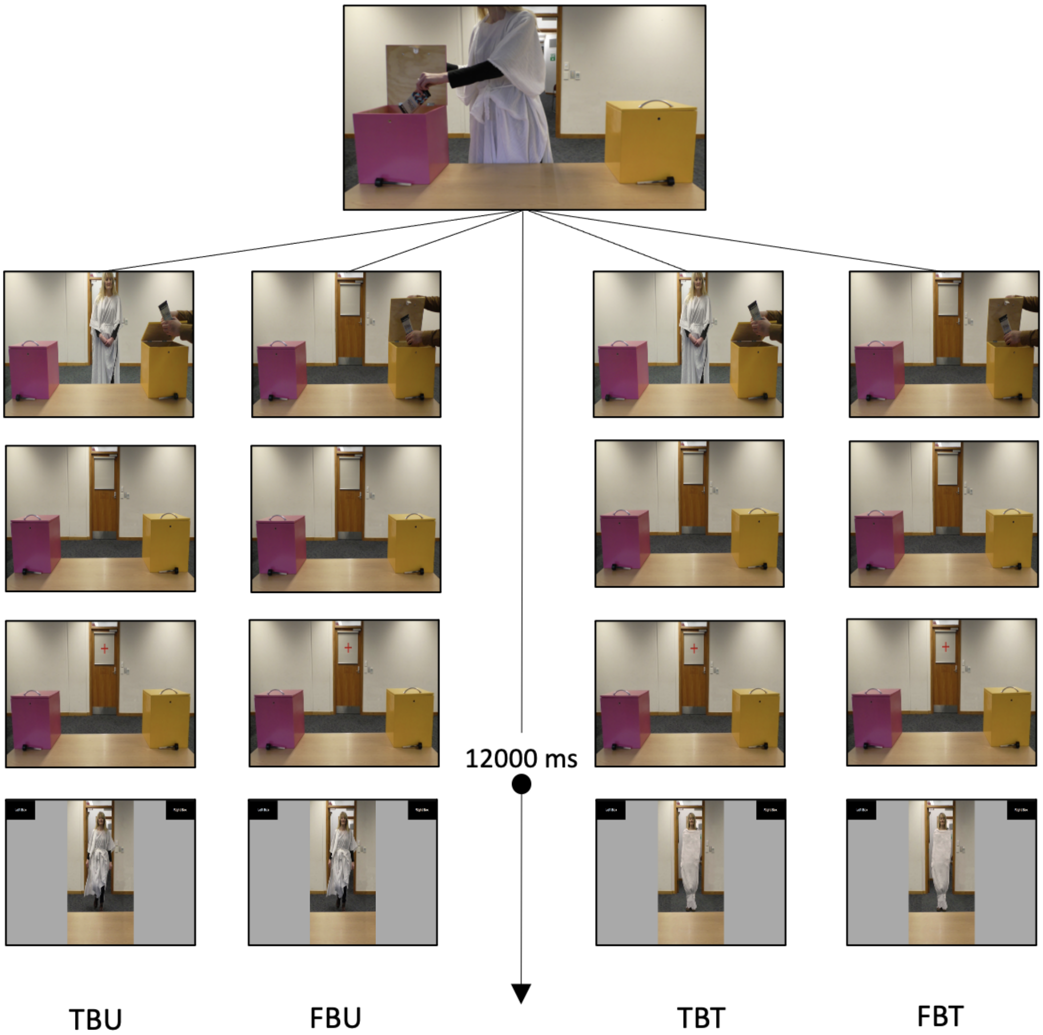


Figure 6.1: *Experiment 3: Times of Events.* *Schematic representation of the relevant events occurring in the True Belief Untied (TBU), False Belief Untied (FBU), True Belief Tied (TBT) False Belief Tied (FBT) conditions. After 12000 ms, the agent came back into the room and participants had click on the top right or top left corner of the screen to indicate the location of the chocolate.*

a) **True Belief Untied** (TBU): after the agent has placed a chocolate bar in one of the two boxes, the experimenter (watched by the agent) moves the chocolate bar from that box to the other. Then the agent leaves the room. After 1200 ms, a beep sound and a fixation cross located at the centre of the door signal that the agent is about to come back into the room. At this point the agent comes back into the room and, as per instructions, participants had to click as fast as possible the box containing the chocolate.

b) **False Belief Untied** (FBU): after placing a chocolate bar in one of the two boxes, the agent leaves the room. While the agent is outside, the experimenter moves the chocolate bar from one box to the other. After 1200 ms, a beep sound and a fixation cross located at the centre of the door signal that the agent is about to come back into the room. At this point the agent comes back into the room and, as per instructions, participants had to click as fast as possible the box containing the chocolate.

c) **True Belief Tied** (TBT): after the agent has placed a chocolate bar in one of the two boxes, the experimenter (watched by the agent) moves the chocolate bar from that box to the other. Then the agent leaves the room. After 1200 ms, a beep sound and a fixation cross located at the centre of the door signal that the agent is about to come back into the room. When the agent comes back into the room it is clear that her ability to move is impaired by bandages blocking her arms and legs. As per instructions, participants had to click as fast as possible the box containing the chocolate.

d) **False Belief Tied** (FBT): after placing a chocolate bar in one of the two boxes, the agent leaves the room. While the agent is outside, the experimenter moves the chocolate bar from one box to the other. At this point the agent comes back into the room and it is clear that her ability to move is impaired by bandages blocking her arms and legs. As per instructions, participants had to click as fast as possible the box containing the chocolate.

6.1.2 Results

6.1.2.1 Mouse Tracker analysis

Participants' responses were recorded with the commercial mice Dell MS116 (1000 Hz, set on the standard medium speed of Windows 10). The mouse-tracking software response boxes were located in the top corners of the screen and were 150 pixels in height and 300 pixels in width. Similar to Experiment 2, before performing formal analysis, I excluded from the dataset all trials (5.26%) in which the initiation time (*IT*, amount of time that the mouse cursor takes to reach a distance of 30 px from the centre of the starting location) was greater than 400 ms. Having an *IT* set at 400 ms is not necessary when running a Mouse Tracker experiment, and some researchers avoid using it altogether (e.g., Kieslich & Hilbig, 2014; Koop & Johnson, 2013), nonetheless it has been described as the optimal cutoff to be adopted when measuring online processes in Mouse Tracker experiments (e.g., Freeman & Ambady, 2009; Hehman et al., 2015). Likewise, all trials (1.04%) in which participants reached and clicked the wrong box (i.e., the now-empty box) were also discarded.

Since all participants had an *IT* below 400 ms in more than 75% of the trials across and within conditions and since they individually showed a good understanding of the instructions by committing <5% of wrong box errors, they were all included in the final analysis.

After checking the raw data for errors and $IT \geq 400$ ms, as per standard practice in mouse-tracker experiments (e.g., Freeman & Ambady, 2010; Koop & Johnson, 2011; Spivey et al., 2005), I remapped all trajectories to one side of the screen and, because raw trajectories varies in duration (and thus they contain a different number of data points), I normalized them into 101 time steps using the linear interpolation provided in the the Mouse Tracker Analyser software (Freeman & Ambady, 2009). Finally, I excluded trials in which the Area Under the Curve (AUC) was deviating more than 2 standard deviations from the average of all trials of that condition and proceeded with the formal analysis.

Before the formal analysis, as a reminder, I predicted to conceptually replicate van der Wel et al.'s (2014) results by finding a difference between the true belief and false belief scenario in the untied condition, with participants' mouse cursor trajectories being more attracted to the empty box in the false belief scenario. Second, I predicted that bodily constraining the agent would disrupt the influence of the agent's belief on participant's hand movements.

For the formal analysis, I entered each participant's mean AUC into a 2 (Belief: True Belief; False Belief) by 2 (Constraint: Untied; Tied) repeated measure ANOVA. Results showed a main effect of Constraint ($F_{1,50} = 5.921$, $p = 0.019$, $\eta_p^2 = 0.106$) with participants' trajectories being generally (that is, regardless of the belief condition) more attracted towards the empty box when the agent was constrained, as revealed by AUC being more positive (but still with a negative sign) in FBT and TBT compared to FBU and TBU. As a reminder, consider that the AUC is the geometrical area between the ideal straight trajectory and the participant's trajectory and it is calculated by summing any curvature heading towards the empty box (computed as positive AUC) and any curvature heading towards the full box (computed as negative AUC). No main effect of Belief was detected ($F_{1,50}$ = 1.48, p = 0.229, η_p^2 = 0.029) nor interaction between Belief and Constraint ($F_{1,50}$ = 0.05, p = 0.825, η_p^2 = 0.001) (see descriptive statistics in Table 6.1).

Table 6.1: *Experiment 3A: mean Areas Under the Curve (AUC) of participants' mouse tracker trajectories in True Belief Untied (TBU), True Belief Tied (TBT), False Belief Untied (FBU) and False Belief Tied (FBT) conditions. The more AUC is negative, the more the trajectory is attracted towards the chosen alternative*

	Descriptive statistics		
	Mean AUC	Std. Deviation	N
TBU	-.098	.118	51
TBT	-.059	.129	51
FBU	-.116	.137	51
FBT	-.084	.165	51

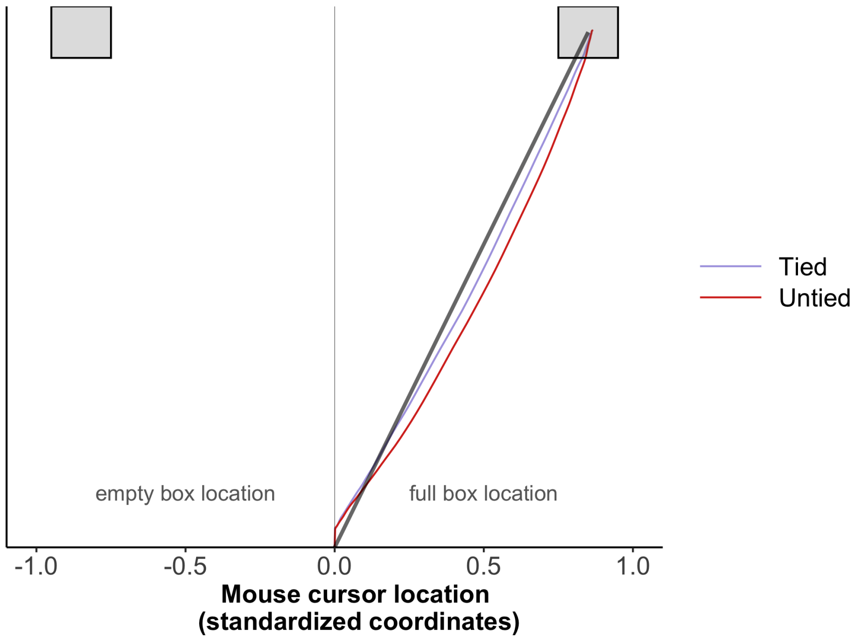


Figure 6.2: ***Experiment 3A: averaged mouse cursor trajectories.*** *Visual representation of averaged mouse cursor trajectories in the TBU, TBT, FBU and FBT. The straight thick line represent the ideal path connecting the starting location with the full box.*

6.1.3 Discussion

In Experiment 3A, I predicted that an agent's irrelevant belief about the location of an object would have influenced participants' mouse cursor trajectories, as found by van der Wel et al. (2014). I also predicted that this influence would have disappeared when the observers' ability to motorically represent an action was impaired by bodily constraining the agent. Differently from Experiment 2, standard-sized response boxes were introduced in the top corners of the screen [similar to van der Wel et al. (2014)]. Further, instead of instructing participants to help the agent, in experiment 3A they were asked to click on the box containing the chocolate. Using standard response boxes was aimed at allowing more time and space for the trajectories to evolve. The helping component of the task adopted in Experiment 2 was instead removed for two main reasons: to reduce the cognitive demands that are usually required in a multiple choice task while isolating the effect of belief tracking on participants' trajectories; and to avoid the confound that a constrained agent who is able to execute a lean motion might have on the observer's motor processing. Nonetheless, these manipulations were not effective in conceptually replicating the results obtained by van der Wel et al. (2014). In line with Experiment 2, participants were generally attracted towards the chosen alternative (see Figure 6.2), as indicated by negative AUC values. Further, I also predicted that, by bodily constraining the agent, participants' trajectories would have been less attracted towards the location where the agent believed the object to be located. The lack of influence of the agent's belief on participants' hand trajectories in the untied condition (i.e., TBU and FBU) makes the effect of constraint not particularly relevant. However, it is worth noting that the constrain did not attenuate the attraction towards the empty box. Participants' trajectories were generally (that is, regardless of the condition) not less but more attracted towards the empty box when the agent was constrained.

Besides the puzzling result suggesting that bodily constraining an agent with bandages makes participants more attracted to the empty box, here the important take away is that I was not able to replicate van der

Wel et al.'s (2014) results. One possible explanation might be that mouse trajectories, similar to other implicit measures for studying belief tracking (e.g., Poulin-Dubois et al., 2018) may be unstable and difficult to replicate. On this regard, it is indeed unusual that since 2014 there has been no sign (not even from the original laboratory) of any replication attempt to replicate van der Wel and colleagues' results. Considering that mouse tracker softwares are freely available to the public and easy to set up, I speculate that replication attempts might have been carried out, but unsuccessfully, and have remained unpublished. Alternatively, it may be that adults in Experiment 3A were not as much motivated in following the sequence of events as in van der Wel et al., or that they did not visually perceive the agent at the crucial response time. In fact, from the participants' perspective, once they saw where the object was last located, they only needed to remember that information and move the mouse after the beep sound. That is, any event occurring after the swap in location was irrelevant to the task. In the same vein, they may have learned that if the chocolate was initially located in one location (i.e., right box), they were going to have to click the other box (i.e., left box) because the location was always swapped. In this case, participant could have lost any motivation to spectate the scene even before the belief induction phase.

6.2 Experiment 3B

The design structure of Experiment 3B was the same as the one implemented in Experiment 3A, except for the addition of an attention check. To ensure that participants were motivated in watching the unfolding of events, and that they visually perceived the agent during the response time window, Experiment 3B was designed with a go/no-go manipulation. The predictions were the same as for Experiment 3A. First, in line with the results by van der Wel et al. (2014), I expected that an agent's irrelevant belief about the location of an object would influence participants' mouse cursor trajectories landing on the actual location of the object. Second, I predicted that temporally impairing motor processes in the observer (by bodily constraining the agent) would disrupt spontaneous belief-tracking, as suggested by recent evidence (Low et al., 2020; Sinigaglia et al., 2021).

It is worth noting that go/no-go tasks are traditionally adopted to study inhibitory control similarly to, for example, the Simon Task (Simon & Wolf, 1963) or the Flanker task (Eriksen & Eriksen, 1974). In go/no-go tasks, participants are required to respond to certain stimuli (i.e., targets) and to withhold their response for other stimuli (i.e., distractors). Typically, the main dependent measure in go/no-go tasks is the commission error rate (responding to "no-go" trials) which provides an indication of inhibitory control (e.g., Meule, 2017). That is, a high rate of commission errors is interpreted as indicative of weak inhibitory control. For instance, hungry participants commit more commission errors when food stimuli are used as distractors compared to control stimuli (Loeber, Grosshans, Herpertz, Kiefer, & Herpertz, 2013). However, differently from their traditional adoption, no-go trials in Experiment 3B were not used to lure participants in making mistakes but rather to ensure that their attention was sustained throughout the duration of the experimental session. In fact, I exploited the fact that when go/no-go stimuli are presented in a fixed location, participants' visual attention is selectively deployed in anticipation of the forthcoming stimuli (Hong, Wang, Sun, Li, & Tong, 2017). Further, since inhibition was not a variable of interest, the cognitive cost of withholding a response to a no-go stimulus was minimised by not using any distractor. Instead, participants were simply instructed to avoid responding when the agent was not in the room. This manipulation was effective, as revealed by a low proportion of commission errors (10.63%).

6.2.1 Method

6.2.1.1 Participants

Fifty-five right-handed adults (M = 19.3 years, range = 17 to 31 years, 45 females and 10 males) were recruited for this experiment. Eight participants were excluded because they did not pay attention, as indicated by more than 25% of commission errors (i.e., execution of go responses in no-go trials). The final final sample of forty-seven participants was more than sufficient to reach the desired power of .80. As in Experiment 3A, G*Power 3.1 indicated that a sample size of 35 would be needed to reach the desired power of .80 for the van der Wel et al. (2014) style of data characteristics (input: f (U) = 0.33, error probability = .05; number of groups = 1, number of measurements = 4).

6.2.1.2 Stimuli and Procedure

The stimuli and procedure were the same as in Experiment 3A (see Experiment 3A Stimuli and Procedure Section 6.1.1.2 for a full description of the experimental conditions and Figure 6.1 above for a schematic representation), except for the inclusion of no-go trials. One no-go trial for each block was added to ensure that participants were motivated to watch the videos and were visually processing the agent in the go trials. The first part of a no-go video sequence was the same as for the experimental videos but it was different after the fixation cross: the agent did not come back into the room and, as per instruction, participants had to avoid responding and wait for the automatic conclusion of the trial.

If participants took $\geq$ 400 ms to move their mouse, a message appeared on screen after they clicked, prompting a faster response in the following trials (i.e., ”Please start moving earlier on, even if you are not fully certain of a response yet”). Further, if participants clicked on the wrong location (i.e., the empty box), the message ”Wrong location” appeared on screen, and if they clicked when they were not supposed to (i.e., in the No Go trials) they were shown the message ”click only if the woman is in the room”.

6.2.2 Results

6.2.2.1 Mouse Tracker analysis

Before performing formal analysis, I excluded from the dataset all trials (12.04%) in which the initiation time (*IT*, amount of time that the mouse cursor takes to reach a distance of 30 px from the centre of the starting location) was greater than 400 ms. Having an *IT* set at 400 ms is not necessary when running a Mouse Tracker experiment, and some researchers avoid using it altogether (e.g., Kieslich & Hilbig, 2014; Koop & Johnson, 2013), nonetheless it has been described as the optimal cutoff to be adopted when measuring online processes in Mouse Tracker experiments (e.g., Freeman & Ambady, 2009; Hehman et al., 2015). Furthermore, similar to Wirth, Foerster, Kunde, and Pfister (2020), I only analysed correct trials. Participants (eight) with more than 25% of commission errors (i.e., execution of go responses in no-go trials) were excluded from all data analysis. Lastly, all trials (3.27%) in which participants reached and clicked the wrong box (i.e., the now-empty box) were counted as errors and discarded.

All participants included in the final data analysis (47/55) had an *IT* below 400 ms in more than 75% of the trials across and within conditions, they had an aggregate of 10.63% of commission errors and they showed a good understanding of the instructions by committing <5% of wrong box errors.

After checking the raw data for $IT \geq 400$ ms, go/no-go performance, and errors, as per standard practice in mouse-tracker experiments (e.g., Freeman & Ambady, 2010; Koop & Johnson, 2011; Spivey et al., 2005), I remapped all trajectories to one side of the screen and, because raw trajectories varies in duration (and thus they contain a different number of data points), I normalized them into 101 time steps using the linear interpolation provided in the the Mouse Tracker Analyser software (Freeman & Ambady, 2009). Finally, I excluded trials in which the Area Under the Curve (AUC) was deviating more than 2 standard deviations from the average of all trials of that condition.

For the formal analysis, I entered each participant's mean AUC into a 2 (Belief: True Belief; False Belief) by 2 (Constraint: Untied; Tied) repeated measure ANOVA. Results showed a main effect of Belief ($F_{1,46}$ = 8.270, p = 0.006, η_p^2 = 0.152) with participants clicking the full box while performing hand trajectories that were more attracted towards the empty box when the agent truly believed that the object was in the full box (TB condition) compared to when the agent falsely believed that the object was in the empty box (FB condition), as indicated by AUC being more positive (but still with a negative sign) in TBU and TBT compared to FBU and FBT conditions. No main effect of Constraint ($F_{1,46}$ = 0.307, p = 0.582, η_p^2 = 0.007) nor interaction between Belief and Constraint ($F_{1,46}$ = 0.067, p = 0.797, η_p^2 = 0.001) (see descriptive statistics in Table 6.2).

Table 6.2: *Experiment 3B: mean Areas Under the Curve (AUC) of participants' mouse tracker trajectories in True Belief Untied (TBU), True Belief Tied (TBT), False Belief Untied (FBU) and False Belief Tied (FBT) conditions. The more AUC is negative, the more the trajectory is attracted towards the chosen alternative*

	Descriptive statistics		
	Mean AUC	Std. Deviation	N
TBU	-.031	.139	47
TBT	-.036	.197	47
FBU	-.070	.149	47
FBT	-.083	.176	47

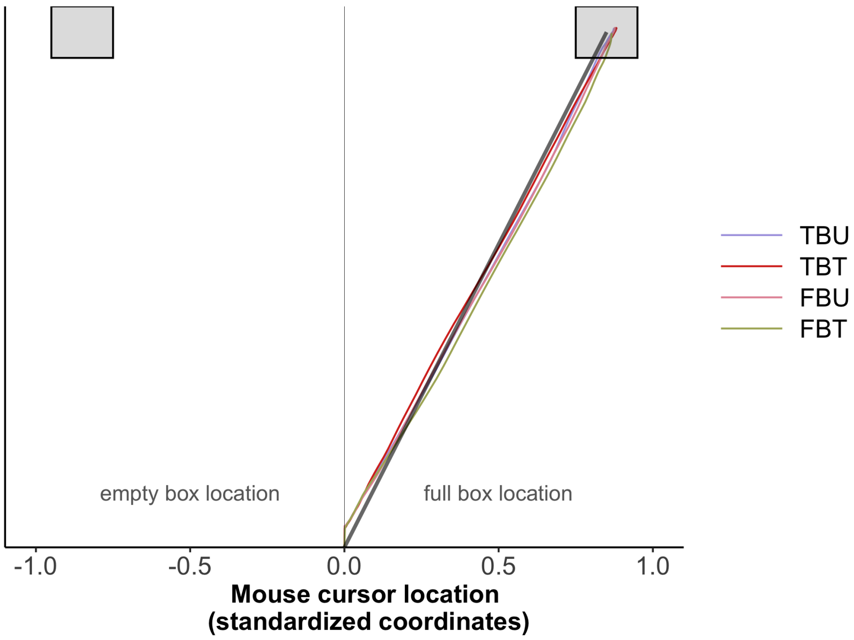


Figure 6.3: ***Experiment 3B: averaged mouse cursor trajectories.*** *Visual representation of averaged mouse cursor trajectories in the TBU, TBT, FBU and FBT. The straight black line represents the ideal path connecting the starting location with the full box.*

6.2.3 Discussion

As of today, the only study using mouse-tracker technology to investigate mindreading processes indicates that adults click the location of a ball with hand trajectories that are influenced by where an agent believes the ball to be (van der Wel et al., 2014). Initial evidence on the efficacy of using hand movements to study efficient belief tracking, and the similarities between the kinematics involved in reach-to-touch actions and point-and-click movements, motivated me in adapting the real-time interaction task that I used in Experiment 1A and 1B to become a computer-based task in Experiment 2, Experiment 3A and Experiment 3B. Since Experiment 2 and Experiment 3A did not detect any effect of the agent's belief on the mouse cursor trajectories of participants who clicked to help (Experiment 2) or clicked the location of the chocolate (Experiment 3A), further modifications to the experimental design were implemented in Experiment 3B.

While participants in van der Wel et al. (2014) had to pay attention throughout all the duration of the trial because the actual location of the target object was only revealed after an initial mouse movement, in Experiment 3A the location of the object did not change after the belief induction phase. For this reason, participants might have not been motivated in paying attention to events leading up to the agent returning into the room visibly constrained or unconstrained. In addition, since the object was always put in one box and then moved into the other box, participants might have learned that they only needed to pay attention to the initial placement to produce a correct response at the end of the sequence. This might have led them to prepare mouse responses even before the belief induction phase, resulting in trajectories that were not influenced by the agent's belief about the location of the chocolate. In Experiment 3B, to ensure that participants paid attention to the scene and that they visually perceived the agent during the crucial time window, I implemented a go/no-go manipulation requiring participants to click the location of the chocolate when the agent came back into the room and to withhold their response when the agent did not come back into the room.

Like in Experiment 3A, I expected that mouse cursor trajectories would have been more attracted towards the empty box when the agent falsely believed the chocolate to be stored in the empty box compared to when the agent knew that the chocolate was in the full box and that impairing participants' ability to motorically represent the agent's goal would have also impaired their fast belief tracking abilities. However, constraining the agent did not influence movement parameters and the main effect of belief had a puzzling opposite direction to what I expected, with participants' trajectories generally (that is, regardless of the constraint) being less attracted towards the empty box when the agent falsely believed that the chocolate was in the empty box. A different way to charaacterise this effect could be that participants in the true belief condition were not more attracted towards the empty box compared to the false belief condition but rather that they clicked the location of the chocolate by moving their mouse with more efficient trajectories that traveled alongside the ideal line connecting the starting location with the box containing the chocolate. In fact, if TB trajectories were actually attracted towards the unchosen alternative, their Area Under the Curve should be positive. On the contrary, as reported in Table 6.2, the Area Under the Curve in TB conditions is negative, although closer to zero (i.e., closer to the ideal trajectory) compared to FB conditions. One possible explanation is that, since all conditions have negative AUCs, participants' hand movements were generally reaching the target by following the shortest path and that the main effect of belief was the result of some noise in the data. Alternatively, it might be that participants in FB condition had to counterbalance their tendency to move towards the empty box to avoid an incorrect response, paradoxically resulting in them having trajectories more attracted towards the full box. In TB condition, the instruction of clicking the box containing the chocolate combined with the agent's true belief did not generate the same conflict, and trajectories were closer to be ideal (see Figure 6.4 for a direct comparison between trajectories in TB and FB conditions).

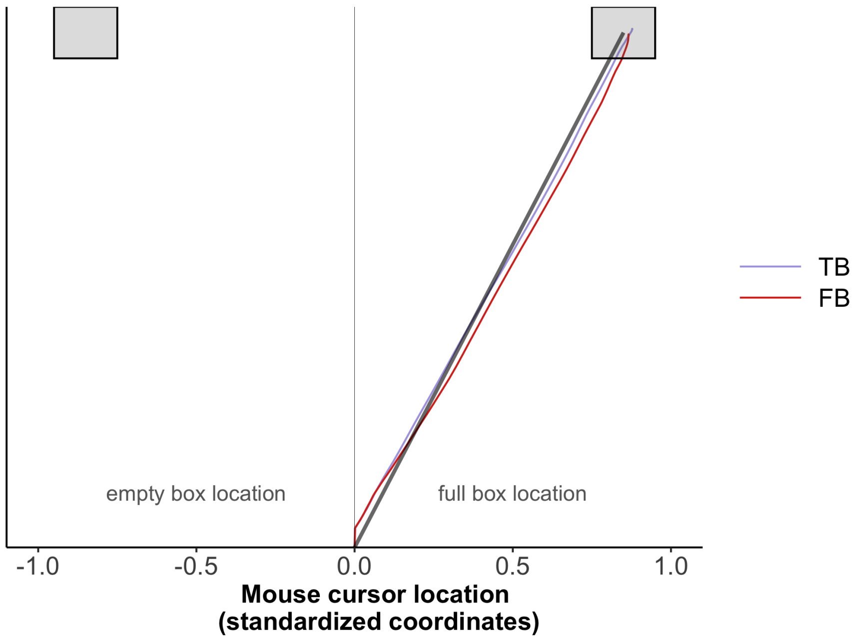


Figure 6.4: ***Experiment 3B: comparison between TB and FB trajectories.*** *Visual representation of averaged mouse cursor trajectories in the TB and FB conditions (with the factor constraint collapsed). The straight black line represents the ideal path connecting the starting location with the full box. Participants' trajectories in FB condition were more attracted towards the box containing the object (or more driven away from the box in which the agent falsely believed the object was located.*

Indeed, it has been suggested that sometimes the suppression of a pattern of motor activity is a mechanism that comes in place to prevent the urge to provide a non-required response (Naish et al., 2014) and that the more motor processes for an action are active, the more those processes are subsequently inhibited (Schuch, Bayliss, Klein, & Tipper, 2010). In Experiment 3B, participants were instructed to watch the unfolding of the events and to click the location of the chocolate, so it is possible to conjecture that a quick and prepotent response to move the mouse cursor towards the (belief-congruent) empty box was prepared, and adjustments took place to prevent a wrong behaviour.

Chapter 7

General Discussion[1]

The aim of the current thesis was to investigate whether and to what extent belief-tracking abilities and motor processes are functionally integrated during action observation. My research was motivated by the conjecture that if motor processes take into account various contextual aspects to guide how action goals are understood, it is conceivable, where that kind of goal ascription occurs in false-belief tasks, for motor representations to incorporate someone's belief-like state. Further, if belief-like states are required to be mapped into the motor system in order for them to appropriately inform the behaviour that is to be expected, disrupting motor processes should undermine the ability to predict the outcome of others' belief based-actions. Drawing from (and combining) multiple methodologies adopted separately in the mindreading and the motor cognition field, I developed a series of experiments to expand on the initial evidence suggesting that

[1]This chapter contains content written by Giovanni Zani from the following published article: Zani et al. (2020)

belief-tracking can operate efficiently (Edwards & Low, 2017; Fizke et al., 2017; Low et al., 2014; Low & Watts, 2013; Wang et al., 2015) and that it might do so by leveraging the motor system's cognitive efficiency (Low et al., 2020; Sinigaglia et al., 2021). The results were mixed.

7.1 Summary of results

Using an adaptation of the Buttlemann helping task (Buttelmann et al., 2009), I started my investigation by measuring adults' belief-tracking and motor processing in two interactive helping experiments (Experiment 1A and Experiment 1B) to test whether motor representations of an observed action take into account an agent's false belief. Experiment 1A confirmed adult observers' FB tracking ability as manifested in certain anticipatory gaze response patterns. In the FB condition, participants looked in anticipation towards the empty box; and in the TB condition, participants looked in anticipation towards the full box. Experiment 1A also confirmed that the information about the agent's belief was processed by spontaneous motor representations. The analyses of adults' mediolateral balance shifts (sampled when there were no overt cues to suggest which box the agent would move towards) indicated that adults leaned towards the empty box in the FB condition; and in the TB condition, they leaned towards the full box. The pattern of participants' eye movements are in line with those studies showing that adults can quickly and correctly anticipate the action of a person who has an FB or a TB about the location of an object (Grainger et al., 2018; Priewasser et al., 2018) and adjustments in adult observers' own mediolateral leaning confirmed the prediction that an agent's registration about the location of the object informs motor processes in the observer. That is, before the agent even performed any overt reaching movement towards a particular box location, observers' motor activity anticipated the likely target of the agent's upcoming action based on where she last registered the object.

Despite eye gaze and leaning showed sensitivity to belief, and although the post-experiment questionnaire indicated that participants were also explicitly aware of where the agent believed the object to be ultimately located, their choice of final helping response was not belief-based. Unlike young children in a similar task (Buttelmann et al., 2009), adults were not more likely to open the full box in the FB condition compared to the TB condition. Instead, regardless of the condition, they helped the other person by opening the box she was directly struggling with (i.e., the now-empty box). Why did they decide that the best way to help was not based on the agent's beliefs? The explanations they provide in the post-experiment questionnaire suggest that the vast majority reasoned about solving a proximal, immediate, problem (e.g., "she was struggling with that box, not the other one"). After all, why should they have decided that the best way to help was based on the other person's beliefs? The fact that the agent last registered the object where it is no more (in FB condition) is only one of the obstacles impeding her action. Another one is her inability to open the box she is directly struggling with. Buttelmann et al. (2009) discuss their results in terms of "correct" and "incorrect" responses in TB and FB, with correct meaning full box in FB condition and meaning empty box in TB condition. However, as Fizke et al. (2017) remind us, for how the events unfold in a Buttelmann et al.'s

(2009) kind of task it is not ”wrong” to help with the proximal goal. In fact, there is not a single correct response.

The main structure of Experiment 1B was the same as in Experiment 1A but the instructions and procedure were modified to explicitly provide a normatively correct way to perform the helping task. In particular, participants were made aware that the agent's upcoming behaviour was going to be guided by the colour of a card she had to draw (which was not shown) at the beginning of the trial. That is, if she drew a yellow card she was going to try to open the box containing the candy and, if she drew a blue card she was going to try to open the now-empty box. Participants were also told that they were going to get a reward if they helped by opening the correct box, the one matching the colour. Crucially, the colour-rule was set before the belief induction phase, so not to give away prematurely that the agent was going to act under a true or false belief. Nonetheless, it required that participants reasoned about the agent's belief in order for them to pass the task. If the agent tried to open the now-empty box in the FB condition, it meant that she was actually trying to retrieve the candy and participants had to open the now-full box; and if she tried to open the now-empty box in the TB condition, it meant that she was doing so for another reason (i.e., because she picked a blue card) and participants had to help her by opening the now-empty box. Against my predictions, the modifications introduced in Experiment 1B were not effective in eliciting belief-based helping behaviour. Replicating Experiment 1A, adult participants' helped the agent with her immediate goal (i.e., by opening the now-empty box). Further, though, the markers associated with belief-tracking (i.e., anticipatory eye-gaze) and motor representation of an action (anticipatory leaning) did not confirm Experiment 1A's findings.

While signs of spontaneous belief-tracking and motor processing emerged in Experiment 1A, it is possible that the colour-rule used in Experiment 1B introduced an additional degree of complexity, which might have been cognitively demanding enough to prevent any spontaneous and efficient interpretation of the scene in favour of a reasoned (and accurate; as reported in the post-experiment questionnaires) approach. Considering the indication that both minimal mindreading and motor processes might depend, at least minimally, to the presence of some cognitive resources, and considering that the complexity of the procedure was not going to be easily solved with additional modifications to the real-time interactive helping task, the paradigm was shifted into a more tightly controlled computer-based task for Experiment 2.

In Experiment 2, I measured adults' final helping behaviour as well as spontaneous belief tracking using a mouse-tracking software and, similar to Experiment 1, I recorded participants' anticipatory leaning on a Wii Balance Board to test whether belief-like states are taken into account when observers generate motor representations of a goal-directed action. The way the events unfolded was fundamentally the same as in Experiment 1: participants watched an agent with either a true or false belief about an object's location trying to open the empty box and then asking for help. As per instruction, participants provided help by moving the mouse cursor and clicking either the now-full box or the now-empty box. I predicted to confirm Experiment 1A's belief-based action prediction in terms of anticipatory leaning on the WBB, and I also expected to conceptually replicate van der Wel et al.'s (2014) results in terms of influence that the agent's belief has on participants' online processing - with mouse cursor trajectories being attracted towards the belief-congruent location. Experiment 2 also tested the prediction that, if belief-tracking is required to pass information to motor representations in order to contribute to action prediction, impairing the observer's motor system should lead to a disruption of belief-based action anticipation. Finally, considering that adults and children have been shown to be inconsistent when it comes to execute a final helping behaviour in a Buttelmann et al.'s (2009) kind of task, I did not make any specific prediction on which box participants were going to prefer to help with. As predicted, in line with Experiment 1A, participants' motor system processed information about the agent's belief to generate accurate behavioural expectations, as indicated by mediolateral balance shifts directed towards the empty box in the FB condition and towards the full box in the TB condition. Crucially, this belief-congruent modulation of the motor representations of a goal-directed action was interrupted when participants' motor system was impaired. That is, WBB results suggest that the agent's inability to move prevented adult observers to generate motor representations of an action, and information about beliefs-like states lacked a framework (at least a motoric one) to express itself. In terms of mouse cursor trajectories, I did not find any evidence of online conflicts between participants' and agent's beliefs. Regardless of the condition, hand movement parameters revealed that choice selection was performed with confidence by reaching the target alongside an ideal straight trajectory connecting the starting location with the chosen box. Finally, Experiment 2 unexpectedly revealed a pattern of adults' explicit helping behaviour that was consistent with Buttelmann et al.'s (2009) original findings with young children: participants chose to help with the full box more in FB condition compared to TB condition when the agent was free to move. Interestingly, the same difference between false and true belief conditions emerged when the agent was constrained. Combined, the WBB and the explicit behaviour results are in line with the conjecture that impairing an observer's ability to motorically represent the outcome to which a belief-based action is directed towards would negatively impact minimal mindreading while sparing flexible reasoning about others' beliefs. In fact, when the agent was motorically constrained, implicit belief tracking was disrupted - as indicated by lack of anticipatory leaning - but participants kept holding the agent's belief into consideration when providing explicit responses.

The results obtained with the mouse-tracker in Experiment 2, contrary to my prediction, were unlike those found by van der Wel et al. (2014). In general, participants helped with trajectories that were not influenced by the agent's belief about the location of the object. To further investigate the possibility that spontaneous belief tracking (and its suppression) is reflected in the way observers resolve conflicts between their own and another person's beliefs during online decision-making, a refined mouse-tracking paradigm was developed for Experiment 3A.

In Experiment 3A, the helping component was dropped and participants watched a change of location scenario with the instruction to click the location of the object. Switching from a helping task to a target detection task allowed me to resolve possible confounds while being able to study belief-tracking and its relation with motor processes in a task more similar to the one implemeted by van der Wel et al. (2014). I expected that participants were going to click on the location of the object with trajectories that were more attracted towards the empty box in FBU scenarios compared to TBU scenarios and that such indication of belief-tracking would be attenuated during the observation of a constrained agent in FBT and TBT. However, the results were in line with Experiment 2. Participants watching an agent who was free to move clicked the location of the object with trajectories that were not influenced by the the other person' beliefs. To account for the fact that, in Experiment 3A, the final location of the object could be inferred just by taking into account its initial placement and without paying attention to the subsequent crucial events, Experiment 3B was conceived with a go/no-go manipulation. By ensuring that participants paid attention to the belief induction phase as well as to whether the agent was either free to move or constrained, I predicted, similar to Experiment 3A, to detect spontaneous belief tracking in the untied condition, with trajectories more attracted toward the empty location in the FB compared to TB condition, but not in the tied condition. While constraining the agent had no effect on the way participants moved the mouse cursor to the target object, an interesting but puzzling pattern of responses emerged when considering how participants processed the other person's beliefs. In contrast to what I expected, when participants and agent had different beliefs about where the object was (i.e., FB condition), the mouse cursor trajectories were not more attracted but more repulsed by the location where the agent falsely believed the object to be located.

Table 7.1: *Summary of results: list of experiments and relative measure which either supported ("Yes") or did not support ("No") the predictions. For the Helping Behaviour column only, "Yes" and "No" indicate a result that was or wan not in line with the original Buttelmann et al.'s original findings. "n.a." is indicated when that measure was not employed. "No*" refers to a result that was not directly in line with the prediction but that could be explained with a model of belief-based action prediction.*

	WBB	Eye-Gaze	Mouse Trajectories	Constraint	Helping Behaviour
Experiment 1A	Yes	Yes	n.a.	n.a.	No
Experiment 1B	No	No	n.a.	n.a.	No
Experiment 2	Yes	n.a.	No	Yes	Yes
Experiment 3A	n.a.	n.a.	No	No	n.a.
Experiment 3B	n.a.	n.a.	No*	No	n.a.

7.2 Discussion

As adults, one way to interface with the social world is by interpreting others' behaviour. We can understand past, current and future actions by inferring another person's mental states such as desires, beliefs or intentions. For instance I could think that "Mark will look for the salt in the right cabinet because he falsely believes that it is still there, while I saw the new flatmate misplacing it in the left cabinet". Reasoning about others' behaviour might appear an ordinary ability. However, how humans are able to sustain fluid social interactions in real-time by accurately anticipating what others are going to do is far from clear. For a long time, the dominant view in the mindreading field has been that, sometimes around the age of 3-4 years, we come to understand that others might act based on beliefs that are different from our own, while younger children and infants are not able to use others' mental states as a frame of reference to interpret actions (e.g., Gopnik & Wellman, 1994; Perner, 1991; Wimmer & Perner, 1983). This position was challenged by increasing evidence obtained with spontaneous-response tasks, which opened the door to the suggestion that sophisticated minds might be developed much earlier, if not present since birth (e.g., Baillargeon, Scott, & He, 2010). Although implicit measures of mindreading abilities have been recently shown to be more difficult to replicate than initially thought (for a discussion, compare Baillargeon et al., 2018; Poulin-Dubois et al., 2018), in the current thesis I have entertained the possibility that fast tracking of false-beliefs are indeed processed by adults as well as by less mature mindreaders, and I explored the possibility that the existence of two-systems of mindreading might explain why both infants and adults show sensitivity to others' beliefs in implicit-tasks while explicit reasoning is only manifested after 3-4 years of age (Apperly, 2010; Apperly & Butterfill, 2009; Butterfill & Apperly, 2013; Low et al., 2016; Low & Watts, 2013; Surtees, Samson, & Apperly, 2016; Surtees et al., 2012). One of the two systems is minimal, cognitively efficient, and present early in life, and the other is later developing, flexible but cognitively effortful. In particular, in my experimental work I tested adult participants to investigate the possibility that, since motor processes can spontaneously guide how the outcomes of an action are predicted (e.g., Rizzolatti & Sinigaglia, 2010), it is conceivable - where that kind of goal ascription occurs in false-belief tasks - for motor representations to account for someone's belief-like state (Butterfill & Apperly, 2016). That is, by leveraging the cognitive efficiency of the motor system, minimal mindreading could be achieved by feeding belief-related information into motor representations and without reasoning about beliefs as such. Further, I tested that, if the ability to track another person's beliefs is deeply incorporated in the onlooker's motor system, temporally impairing motor processes in the observer would not allow to efficiently process an agent's belief-like state, ultimately disrupting how behavioural expectations are generated (Butterfill, 2019; Butterfill & Apperly, 2016; Low et al., 2020; Sinigaglia et al., 2021).

There is some related evidence in the literature showing that motor representations are involved in tracking others' bodily position, and that this kind of motor representations can facilitate perspective-taking, particularly when one own's body orientation in relation with the objects in the scene is similar, rather than different, to the other's body orientation (Kessler & Thomson, 2010; Surtees, Apperly, & Samson, 2013). More direct support to the conjecture that the motor system is deeply implicated in mindreading comes from recent reaction times studies showing that participants spontaneously take into consideration an agent's irrelevant belief when he is able to move but not when he is physically constrained (Low et al., 2020; Sinigaglia et al., 2021). A even stronger indication that belief-tracking and motor representations are indeed tightly integrated would, of course, need to come from evidence gathered from multiple sources. For this reason, I tested whether and to what extent mindreading and motor processes are functionally related using different techniques. As laid out in the previous section, and reported in Table 7.1, the results were mixed.

Taken together, my findings indicate that there are cases in which fast tracking of others' beliefs interfaces with motor processes, to the extent that it can influence motor representations of an action and facilitate accurate action anticipation. In Experiment 1A and Experiment 2, adjustments in adult observers' own mediolateral leaning suggest that motor representations and processes can successfully accommodate cases where belief-tracking informs goal ascription. In the FB condition, adults leaned towards the empty box; and in the TB condition, they leaned towards the full box. The fact that adults leaned to their own right side in anticipating that the agent would - from her perspective - go to the left-side box, and that adults leaned to their own left side when anticipating that the agent would - from her perspective - go to the right-side box, fits with computational and conceptual models suggesting that motor representations and processes may be able to remap the agent's allocentric frame of reference into subjects' own egocentric frame of reference (Oh, Braun, Reggia, & Gentili, 2019). There are, however, studies showing that the link between action observation/prediction and action execution can be motorically mapped in some somatotopic manner (e.g., see Fadiga, Craighero, and Olivier (2005) for a review). For example, adults observing a needle penetrating the hand of a human model showed changes in corticospinal motor representations in the particular muscle that was pricked (Avenanti, Bueti, Galati, & Aglioti, 2005). Adults also show action priming effects when congruent body effectors are involved (Brass, Bekkering, Wohlschläger, & Prinz, 2000). Nonetheless, there is also more to the dynamics of motor representations and processes. Many studies show that there is selective discharge in motor activity according to the goal an action is directed towards, regardless of the specific effector used (Cattaneo et al., 2010; Rizzolatti & Sinigaglia, 2010). For example, adults observing someone wearing a miniaturized soccer shoe kicking a ball with the index finger showed motor facilitation in their leg (Betti et al., 2015). There is broader evidence, then, that lends weight to my findings, suggesting that motor representation and processing of another's action towards an object is not just a matter of muscle, effector or posture specific resonance but, more importantly, of the belief-informed goal another's action is directed to.

The same pattern of anticipatory eye-gaze and leaning was not consistently observed across all the experiments. In fact, in Experiment 1B, participant did not look in anticipation of an agent's beliefs about object location and they did not motorically represent the goal of the observed action. The lack of anticipatory eye-gaze could be interpreted as an indication that belief-tracking is not cognitively efficient (Schneider et al., 2012), or even that it does not exist at all (e.g. Kulke et al., 2019; Kulke et al., 2018), specially if we consider a process to be cognitively efficient only when it is automatic, stimulus-driven and completely independent from cognitive resources. While there is evidence that tracking another person's belief can be done rapidly and involuntarily (e.g., Samson et al., 2010; van der Wel et al., 2014) and under cognitive load (Qureshi et al., 2010), other authors find that secondary tasks (Schneider et al., 2012) and emotional states (Bukowski & Samson, 2016) can cause a cognitive turbulence that affect even the simplest forms of implicit mindreading. As O'Grady, Scott-Phillips, Lavelle, and Smith (2020) remind us, it is possible that the kind of automaticity criterions imposed by opponents (Kulke et al., 2019; Kulke et al., 2018; Schneider et al., 2012) as well as proponents (Apperly & Butterfill, 2009) on efficient mindreading might be too stringent. Thinking in extremes, if minimal mindreading had to depend on a tight definition of automaticity, that is, on being stimulus-driven and unavoidable, one single evidence of lack of anticipatory behaviour in a task involving belief-related stimuli might be sufficient to jeopardise its existence. Alternatively, then, it might be more appropriate to think of efficient, minimal, mindreading as *spontaneous* rather than fully fledged automatic: its functioning might be largely characterised by fast and unconscious processing of the scene which, unlike automatic processes, depend on basic attentional resources. We can think at this difference as the contrast between "seeing in colour, which is automatic, [and] seeing in focus, which is spontaneous: it occurs only as and when necessary, as determined by attention" (O'Grady et al. 2020, page 1608). Experiment 1B saw participants interact in real-time with an agent in a belief-based context that was credible, but complex, or more complex than Experiment 1A and Experiment 2, to the extent that attention might have been channelled towards processing unusual aspects of the scene other than belief-like states. In this way, elements that are crucial for the engagement of the efficient system of mindreading, such as where the other person last registered the object, might have been left out of focus, resulting in the lack of anticipatory eye-gazing. We should also consider that, if the observer's motor system can generate representations of an observed action taking into account facts about the reality as registered by the agent (Apperly & Butterfill, 2009), lacking information about such registrations should have resulted in behavioural expectations that were fixated on the goals and that disregarded the agent's beliefs. That is, participants in Experiment 1B should have leaned towards the box containing the object regardless of the agent's beliefs. Instead, they did not show any anticipatory leaning. This is not surprising though when considering that motor processes and representations are also disrupted under cognitive load (Chong et al., 2009) and that, although sometimes described as inevitable (e.g., Iacoboni et al., 1999), they depend on attention being overtly (Bach et al., 2007), or at least covertly (Puglisi et al., 2018), oriented on the action. One possibility is that the combined absence of implicit eye-gaze and anticipatory leaning might suggest that contextual distractors in the environment selectively prevent the motor system to code for the another person's actions and, as a consequence, belief-related as well as goal-related information have no structure to efficiently map onto. Nonetheless, it is not possible to exclude that, in Experiment 1B, a lack of sufficient attentional resources might have negatively impacted both mindreading and motor processes, separately. To test whether or not mindreading and motor processes are two separate and independent processes, more research is needed and one possibility might indeed involve diverting attentional resources away from, for instance, only the motor processes to see whether minimal belief-tracking is preserved or whether it is dependent on the motor system's efficiency to express itself. Experiment 1B was not set up to do so and, considering that converging evidence gathered separately in the mindreading and the motor cognition field suggests that cognitive load can disrupt belief-tracking as well as motor processes, designing a task that unequivocally disrupts the access to resources to one process but not the other might be difficult. A more direct approach, and one that I implemented in my research, is to select a manipulation that is known to selectively disrupt motor processes and to measure the effects on spontaneous mindreading.

Research on motor processing suggests that an onlooker's motor system generates expectations taking into account facts about the actual environment (e.g. barriers that might block someone's possibility to act in reaching space) (Rizzolatti & Fogassi, 2014). Such motor processes occur not only when a subject is observing an actual environment but also when she or he is imagining it (Jeannerod, 2006). Butterfill and Apperly's (2016) suggestion that, during action observation, the onlooker's motor system is not tied to the actual environment but can also generate behavioural expectations based on the agent's beliefs could be seen as supported by Experiment 1A and Experiment 2 findings. However, if belief-tracking and motor processes are tightly integrated in the way that Butterfill and Apperly envisage, and one is not just the byproduct of the other, impairing subjects' abilities to represent actions motorically by using bodily constraints (Ambrosini et al., 2012) should also interfere with belief-tracking. In line with recent reaction time studies (Low et al., 2020; Sinigaglia et al., 2021), in Experiment 2, adults' leaning on a WBB reliably reflected the agent's beliefs when the agent was free to act, as discussed above, but crucially not when the agent was visibly constrained. The disruption of belief-based mediolateral leaning when manipulating the agent's ability to move lends weight to the suggestion that mindreading and motor processes are tightly integrated. Experiment 2 findings converge with studies showing that the ability of the observer (e.g., Ambrosini & Costantini, 2013; Ambrosini et al., 2012; Costantini, Ambrosini, Tieri, Sinigaglia, & Committeri, 2010), as well of the agent (e.g., Buccino, Sato, Cattaneo, Rodà, & Riggio, 2009; Cardellicchio, Sinigaglia, & Costantini, 2013; Costantini, Committeri, & Sinigaglia, 2011; Maranesi, Bonini, & Fogassi, 2014), to act provides a foundation for planning one own's actions or predicting the future behaviour of others. For instance, Buccino et al. (2009) documented a weaker motor facilitation during the observation of a mug with a broken handle; faster reaction times are induced only when the object is perceived as reachable, by the observer (Costantini et al., 2010) or by the agent (Costantini et al., 2011). And not only physical, but also imagined constraints modulate the way the motor system represent actions: we take longer to perform, but also to think about performing difficult actions (Decety & Lindgren, 1991). Then, on the one hand, my findings are in line with Low et al. (2020) and Sinigaglia et al. (2021), and suggest that motor processes and representations in the observer can carry information about beliefs during action observation, and that the way anticipatory leaning is sensitive to belief-based actions can be modulated by disrupting the agent's possibility to act. On the other hand, the use of the WBB for answering questions about belief-based action understanding is novel, and the converging evidence I sought by measuring whether belief-congruent effects on participants' mouse cursor trajectories (van der Wel et al., 2014) disappear when adult observers can not motorically represent the agent's goals was inconclusive.

Before discussing the reason why I consider the mouse-tracking data that I collected as inconclusive, allow me first to briefly direct the reader's attention towards an effect that, although unexpected, has been discussed in the motor cognition literature as suggestive of motor representation of an observed action. In Experiment 3B, contrary to my predictions, participants - who knew the true location of the object - clicked the box containing the object with mouse cursor trajectories that were not more attracted but more *repulsed* by where the agent falsely believed the object to be located (i.e., FB condition). This could indicate that motor representations for the other person's expected action (i.e., that she will go to the box she believes contains the object) were not more active but inhibited, which might sound counterintuitive, and it is. In fact, an observed action is usually thought to be facilitating rather than inhibiting the motor representations for that action. Nonetheless, studies using EEG (e.g., Schuch et al., 2010), TMS (Betti, Castiello, Guerra, & Sartori, 2017; Villiger, Chandrasekharan, & Welsh, 2011) or a combination of EEG and TMS (e.g., Hummel, Andres, Altenmüller, Dichgans, & Gerloff, 2002) have referred to this phenomenon as a *post-stimulus rebound* effect that reflects inhibition following the activation of the motor system. Think about a funambulist who is trying to keep an appropriate balance on a rope. Just when he is about to fall on his right, he counters the not-anymore required (if not dangerous) rightward movement by moving leftwards. However, while inhibiting the rightwards movement using a counter movement to his left, he can over do it, ending up rebounding on the left side of the rope. Schuch et al. (2010) show that mu rhythm enhancement (associated with decreased mirror neurons activity) is larger at the end of an observed action that is relevant to the observer's task compared to when the action is irrelevant. In their task, participants had to watch a reach-to grasp action that was performed on a mug with either a precision grip or a whole hand grasp and they were instructed to attend to the action or to attend to the colour of an over-imposed cross. Compared to when participants had to attend to the colour, when they had to attend to the action the mirror system became more activated (i.e., typical mirror effect) but it also became more inhibited after the disappearance of the stimulus (i.e., post-rebound effect). The authors argue that this rebound reflects inhibition of a previously activated - and "now" unnecessary - representation of an action, and that its power is directly related to the previous activation of the motor system. Thus, when the observed action is relevant to the observer, such as when participants in Experiments 3B are representing that the best way (that is, from the agent's point of view) to retrieve the object is to go to the empty box, the observer's motor system becomes more activated for a movement towards the empty box (as we saw in Experiment 1A and Experiment 2's anticipatory leaning) and subsequently, such as when the agent's goal is irrelevant to participants that are instructed to click on the location where they know the object is, it becomes more inhibited.

Regardless, the mouse-tracking results in Experiment 2, Experiment 3A and Experiment 3B were unlike those obtained by van der Wel et al. (2014) in a conceptually similar task: participants' trajectories were not attracted towards the box in which an agent who was free to move believed the object to be located. Then, since the mouse tracker did not produce the predicted belief compatibility effect in terms of curvature attraction towards the box in which the agent - truly or falsely - believed the object to be located, I could not test the impact of motor disruption on an effect that simply was not there. Whereas it might be tempting to conclude that my failure to conceptually replicate van der Wel et al. (2014) deals an additional blow to the existence of implicit minderading, I believe that a more cautious approach is in order. The use of mouse-tracking techniques to explore parallel activation has been implemented in a wide variety of domains of psychological science such as language processing (e.g., Spivey et al., 2005), cognitive control (e.g., Erb, Moher, Song, & Sobel, 2017), deception detection (e.g., Monaro, Gamberini, & Sartori, 2017; Sartori, Zangrossi, & Monaro, 2018), user experience research (Monaro, Negri, Zecchinato, Gamberini, & Sartori, 2021) (for a review, see Erb, 2018) but has not yet appealed to researchers in the theory of mind field. In implementing the use of mouse-tracking technology, then, I based my methodology on the only one study that has investigated how people keep their own and an agent's belief in mind in parallel (van der Wel et al., 2014). However, the fundamental nature of my tasks was different from van der Wel et al.'s and did not allow for a close replication. In fact, while van der Wel et al. (2014) used an adaptation of Kovac's ball detection task (Kovacs et al., 2010), whereby the agent is a passive observer of the events, my tasks were characterised by an agent having a manifested agency on the scene (i.e., the agent interacts with the object) and by participant having a sense of interaction with the agent. While in both cases, after the belief induction phase, the agent came back into the room and participants were required to move their mouse and click on a response box as quickly as possible, the location of the target object did not change during the response time window in my experiments but it did so in van der Wel et al.'s task (i.e., after an initial mouse movement the occluders dropped and revealed the actual location of the ball).

The different strategies required to perform these different tasks might explain why van der Wel et al. (2014) found online processing of an agent's beliefs while I did not. Permit me to explain further. In a typical mouse tracker experiment, participants can be instructed to provide their response with a deadline, static or dynamic start procedure. In a *deadline start procedure*, participants click the start box to begin the trial, the stimuli appear immediately and participants are instructed to respond early, or as quickly as possible. In a *static start procedure*, participants click the start box to begin the trial, the stimuli appear immediately and no time restrictions are imposed on response initiation. Finally, in a *dynamic start procedure*, participants click the start box and the stimuli appear after participants have moved the cursor upwards. Although a meta-analysis conducted on 160 studies shows that the static starting procedure is the most commonly used (60%) (Schoemann, O'Hora, Dale, & Scherbaum, 2021), allowing participants to take all the time they want to take a decision could result in their response ultimately reflecting an offline response selection rather than an online cognitive process. On the contrary, a dynamic response selection - used in 8.13% of the studies considered by Schoemann and colleagues - forces participants to initiate a movement in condition of uncertainty, and to quickly resolve parallel representations - such as where I last registered the object versus where you last registered the object - based on information that is presented online. Why might the difference between static and dynamic procedures be important for us? After all, both my set of experiments and van der Wel et al.'s study required participants to provide their response as quickly as possible. By definition, they should be considered to have a deadline start procedure. Not quite. I believe that my procedure was conceptually more similar to a static procedure, that van der Wel et al.'s was more similar to a dynamic procedure and that the different approaches might explain the different results. In Experiment 2, Experiment 3A and Experiment 3B, participants clicked the start button, a trial begun, and a series of events unfolded, ultimately resulting in the agent having either a true or false belief about the location of an object. Crucially, the object was moved in its final location early in the sequence (i.e., 6000 ms before response time in Experiment 2; 3600 ms before response time in Experiment 3A and Experiment 3B). Consequently, participants, although instructed to move the mouse as quickly as possible, had all the elements to reach an informed decision early, offline. That is, they might have not needed to solve conflicts between their own and the agent's beliefs during the response time window because they had already done so earlier. On the contrary, participants in van der Wel et al. (2014) could not strategically decide to click the right box as opposed to the left box early in time because the actual location of the object was revealed only after an initial upward mouse movement. As as result, participants had to execute cursor movements while processing the relevant information and while holding their own and the agent's beliefs in parallel, ultimately resulting in mouse cursor trajectories being reflective of contrasting beliefs about the location of the object. There is extensive support to the view that mouse cursor trajectories can be significantly affected by the type of response procedure implemented (e.g., Scherbaum & Kieslich, 2018; Schoemann, Lüken, Grage, Kieslich, & Scherbaum, 2019; Schoemann et al., 2021). For instance, Schoemann et al. (2019) show that it is possible to find drastically different results if two identical tasks applying a static procedure as opposed to a dynamic procedure. The authors show that, similar to my Experiment 2 Experiment 3A and Experiment 3B, trajectories in a static procedure task go straight to the chosen option - without curvature - and do not reflect the online attraction effect observed in an identical task using a dynamic procedure.

In conclusion, I urge caution in the interpretation of the current work. On the one hand, the results confirm that information about beliefs can be efficiently processed by the motor system to generate accurate behavioural expectations (Experiment 1A and Experiment 2). On the other hand, the limited data I was able to gather in terms of whether or not a motor disruption negatively impact mindreading leaves the door open to alternative interpretations regarding how exactly belief-related information feed into motor representations. It is suggestive to show that disrupting an observer's ability to generate motor representations of an action interferes with widely replicated belief-tracking in a ball detection task (Kovacs et al., 2010; Low et al., 2020; Sinigaglia et al., 2021) as well as with more novel and interactive ones (Experiment 2), but there is still much work to be done to understand the scope of efficient mindreading in our social lives.

7.3 Alternative Interpretations

The aim of the current thesis was to test whether and to what extent belief-tracking is functionally related to motor processes during action observation and understanding. I have argued that my findings offer some support to Butterfill and Apperly's (2016) conjecture that planning-like motor processes in the observer generate behavioural expectations by taking into account not only facts about the actual environment but also facts about the environment as specified by the agent's registrations. The results I found in Experiment 1A and Experiment 2 with adult participants extend the broader evidence suggesting that motor representation and processing of another's action is not just a matter of muscle, effector or posture specific resonance but also of goals and the best way to achieve them. However, I also have to consider whether my finding could be better explained by alternative interpretations.

First, while there is general agreement that an observer's motor system becomes active both during action execution and action observation, there is no consensus about whether motor representations allow the observer to identify the outcome to which an observed action is directed or whether they reflect, at best, specific low-level features of the kinematics involved in the movement (for reviews, see Gallese et al., 2011; Glenberg, 2011; Heyes & Catmur, 2022). Second, if exploitation of motor processes do allow us to achieve fast action anticipation by representing the best way (i.e., the best way based on physical and non-physical constraints of the environment) to do something now to achieve something later, can my data support the view that sometimes the only representations required for belief-based goal ascription are motor representations (Butterfill, 2019; Butterfill & Apperly, 2016; Low et al., 2020; Sinigaglia et al., 2021)? Or can my finding be better explained by considering minimal mindreading as relying on the same kind of cognitive resources as the ones extensively used during explicit mindreading (e.g., Carruthers, 2016, 2017; Scott & Baillargeon, 2017)?

It is controversial whether motor activation during action observation strictly reflects the kinematics of the observed action or whether it can accommodate the more higher-ordered goals (for a discussion, see Gallese et al., 2011). Some authors argue that mirror neurons contribute to low-level action recognition but not to higher-level processes such as matching an action to the relevant object in a given context (e.g., Catmur, 2014; Heyes & Catmur, 2022; Thompson, Bird, & Catmur, 2019). However, while muscles involved in the observed action appear indeed to be strictly matched in the observer (for a review, see Fadiga et al., 2005), there are also studies showing that the more abstract features of an action can be extracted from movement parameters such as speed, trajectory or grip aperture of a hand reaching for a target (Cavallo, Koul, Ansuini, Capozzi, & Becchio, 2016; Sartori, Becchio, & Castiello, 2011; Soriano, Cavallo, D'Ausilio, Becchio, & Fadiga, 2018; Thioux et al., 2018). For example, participants in Sartori et al. (2011) are fast and accurate in judging whether the initial motoric cues of an agent who is reaching for an object indicate that he will use the object to cooperate as opposed to perform an individual action. Nonetheless, Thompson et al. (2019) warn about interpreting results obtained using reach-to grasp actions whereby both kinematics and goals vary: a problem with these studies is that it is difficult to disentangle if the data reflect attribution of different goals or, instead, representation of movement kinematics without goal ascription.

The fact that motor simulation in the observer has been traditionally studied by using tasks that measure the effect of kinematic cues (e.g., hand pre-shaping) on action anticipation makes it hard to design a control condition that is missing only the kinematics or only the goal without introducing confounds (Grafton & Hamilton, 2007). Although the experiments adopted in the current thesis were not specifically designed to test the different contribution that the kinematics and the goals have in action anticipation, I measured observers' motor activation when there were no motor cues to suggest which box out of two identical boxes the agent was going to reach for. Then, if the claim that, at best, the motor system represents low-level motor features involved in the observed action, participants in Experiment 1A and Experiment 2 should have not shown any rightwards-leftwards anticipatory leaning. In fact, during the crucial time window, the agent came back into the room walking on a straight trajectory, without showing any indication about which box she would have ultimately moved towards. Instead, participants spontaneously leaned towards the box in which the agent believed the object to be located, towards the empty box in the FB condition and towards the full box in TB condition. Regardless, Grafton and Hamilton's 2007 broader suggestion that the motor (and mindreading) field needs novel approaches that can better isolate the different level of an action, remains valid.

If connections between motor and mindreading processes allow us to understand situations where belief-tracking informs goal ascription, then this is useful for social cognition. But how should we characterise the connections? One possibility is that mindreading and motor processes are tightly integrated and that, sometimes, the only representations required for accurate behavioural expectations in a false-belief task are motor representations. As I have discussed throughout the current thesis, this view is motivated by evidence that the cognitive efficiency of the motor system is well suited to accommodate low-level information about the kinematics of observed actions, as well as the physical and not physical aspects of the environment in which they occur. In this case, the mechanism behind goal ascription might be characterised either by the activation of these fine grained low-level representations propagating to the higher-ordered goals in a bottom-up fashion (e.g., Rizzolatti et al., 2001), or by having each hierarchical level of the action (e.g., muscular, kinematic, goal level) constantly updating online, based on how the action unfolds, until the most appropriate behavioural expectation is achieved (Kilner et al., 2007; Sinigaglia & Butterfill, 2016); (for a model of how actions can be hierarchically structured, see Grafton & Hamilton, 2007). Alternatively, it might be that beliefs are interpreted outside the motor system, and that motor representations are activated only after high-level goal ascription. For instance, Csibra (2007) suggests that the low-level characteristics of an action, such as its kinematics, are reconstructed at a motor representations level on the basis of previously generated interpretations of the goals. That is, only after the goals are understood, motor simulation can occur. An account of action mirroring that consider observed actions as being interpreted to the highest possible level before they are mapped on to the motor system would be consistent with the view that understanding others' beliefs has to be an inferential and sophisticated ability (Onishi & Baillargeon, 2005) rather than a cognitively efficient process that can be achieved with motor representations only (Butterfill & Apperly, 2016). Further, considering that action mirroring occurs not only in adults but also in the less mature infants (Southgate, Johnson, Osborne, & Csibra, 2009) and monkeys (e.g., Fadiga et al., 1995), if Csibra is right, it could be argued that, early in life, a high-level and fully fledged false-belief understanding is present, modulating the motor system in a top-down fashion. In other words, under this lens, belief-tracking is a process that generates behavioural expectations independently from the motor system and before its activation. Accordingly, it is possible that participants in Experiment 1A and Experiment 2 leaned in anticipation towards the box in which they expected the agent to go not on the basis of spontaneous belief-based motor representations, but based on action interpretation that then triggered emulation of those motor plans required to reach the already represented outcome. The same kind of reasoning could be arguably used to explain the results found by Low et al. (2020) and by Sinigaglia et al. (2021), whereby the agent's belief about the location of the ball is induced early in time, well before response time. However, there is also data showing that the timing of a visually presented action and the activation of the relevant motor representation in the observer is equivalent, not leaving time for slow inferential processes (e.g., Becchio et al., 2012; Buccino et al., 2009; Buccino et al., 2004; Mukamel et al., 2010). Then, if we consider the cases in which the time course of motor representations does not allow for inferential processing in combination with the preliminary results showing that belief-related information can be mapped in a motoric format (Experiment 1A and Experiment 2), Butterfill and Apperly's 2016 conjecture that, other than generating high-level inferences interpretation of the social world, humans can use their motor system to make spontaneous predictions based on others' belief-based actions remains valid. However, while the evidence points in the direction of the existence of multiple routes available to mindreading (Samson & Apperly, 2010), the causal contribution of the motor system will have to be further explored with tasks specifically focused on the evolution in time of belief-tracking.

7.4 Future Directions

The experimental work of the current thesis was initially committed to viewing Buttelmann et al.'s (2009) real-time interactive helping task as having potential for testing adults' spontaneous motor processing in the understanding of others' actions. I reasoned that its change-of-location component combined with the presence of an agent performing purposive actions made it a suitable candidate to study belief-tracking abilities as well as spontaneous motor processes. However, considering that the pattern of explicit helping behaviour I found in Experiment 1A Experiment 1B and Experiment 2 was not consistently in line with the classic Buttelmann's findings, I endorsed the view that there is no normatively correct helping response in a Buttelmann et al.'s interactive helping task (Crivello and Poulin-Dubois, 2018; Fizke et al., 2017; Priewasser et al., 2018; but see Baillargeon et al., 2018) and I decided to adopt a task that did not measure explicit behaviour when designing Experiment 3A and Experiment 3B. A question, then, is whether future studies aimed at studying adults' spontaneous fast belief-tracking and spontaneous motor processes could benefit from using tasks that closely replicate Buttelmann et al.'s methodology. My view is that this particular kind of helping tasks should be avoided when explicit reasoning is not a variable of interest. In fact, eliciting participants to help in a task in which multiple correct ways of helping are available poses the risk that the inferential decision process might act as a confound. For instance, its occurrence could temporally overlap with the measuring of implicit processes and divert the attention away from the salient aspects of the action (for discussions on task complexity and its implication for spontaneous processing of social stimuli, see Bach et al., 2007; Puglisi et al., 2018; Samson & Apperly, 2010). This does not necessarily mean that any manipulation that increase participants' involvement in a social interaction should be avoided, and the adoption of paradigms that are more ecologically valid than computer-tasks should be taken into consideration when studying action observation (e.g., Becchio, Sartori, & Castiello, 2010; Reader & Holmes, 2016). The real-time task developed by Buttelmann and colleagues provides a good methodological starting point to jointly study belief-tracking and motor processes but, while creating a setting that is as naturalistic as possible, future studies should develop real-time approaches which tap into implicit forms of social cognition by minimising sources of possible confounds.

Regardless of whether future experiments adopt a real-life scenario or a computer-based task, researchers should also tackle the challenge of whether belief-tracking is achieved through motor processing or whether it is a separate, independent, mechanism. This could be achieved by exploring the time sequence of their occurrence. In fact, an issue with my experiments, but also with Low et al. (2020) and Sinigaglia et al. (2021), is that the belief induction phase precedes the measurement of motor processes, leaving the door open to the possibility that belief-tracking is achieved early, perhaps through inferential processing, and that an already-coded information is then passed to the motor system. Therefore it remains possible to argue that getting rid of the ability to motorically represent the goal of an action prevented implicit belief-tracking from having a motor ”voice”, but not necessarily from existing and being expressed elsewhere that neither I nor colleagues were able to detect. In other words, while the evidence gathered so far indicates that registrations about beliefs can be mapped into a motoric format, we do not know yet how to characterise the way they are originally coded. If it turns out that implicit belief-tracking in adults can be achieved independently from motor processes, this would not automatically exclude the possibility that there are cases in which the only representations required for fast spontaneous belief-tracking are motor representation. However, to test the possibility that belief-tracking is sometimes so tightly dependent on motor processes that the two could be seen as the same process, future studies should focus on whether the motor system, as much as it can update motor representations of an observed action online, for instance at the precise moment when a movement from being non-social becomes social (Sartori, Bucchioni, & Castiello, 2013), can also code based on sudden changes in the agent's beliefs. Considering that motor imagery invoked by linguistic stimuli influences motor representations and the way listeners automatically sway on a balance board (Zwaan et al., 2012), for instance they lean backward when hearing "The teenager plopped down on the couch", timing sudden action representation with sudden belief-induction could be achieved by having participants hearing "The teenager sits down on the chair" at the same moment they see the chair being either secretly or openly pulled away. If motor representations of an action represent the best way (from the teenager point of view) to do something now (leaning backward) to achieve something later (sit on the chair), backward-leaning should be observed in participants' swaying when the teenager knows the chair is there and when he falsely believe is there, but not when the teenager truly believes the chair is not there anymore. Of course, this is just a sketch idea but, if it could be demonstrated that adults' motor system actively track registrations of beliefs, rather than represent the result of an external belief-tracking process, such ability would go a long way to explain how for adults, as for infants, it is possible to manage sensitivity to others' beliefs with limited cognitive resources.

New paradigms that effectively tap into online processing of other persons' beliefs by accurately timing the sequence of events would also be beneficial for an appropriate implementation of mouse-tracking methodologies, which are traditionally adopted for studying parallel activation of different, and sometimes contrasting information. In my experiments, the belief induction phase preceded participants' mouse response onset by 6000 ms in Experiment 2 and 3600 ms in Experiment 3A and Experiment 3B. This might have caused an early, offline, resolution of the conflicting informations between what participants believed and what the agent believed, ultimately resulting in mouse cursor trajectories that did not reflect anything other than a confident motion towards the target object, as discussed in section 7.2. Instead, aligning the response time onset with a sudden belief induction, combined with instructions requiring participants to move the mouse early, would allow researchers to study how online belief processing affects ongoing motor activation and responses. A further improvement to studies that aim at investigating action observation and action execution by measuring continuous hand movement trajectories could be achieved by implementing alternative techniques that do not involve the use of a computer mouse. In fact, while mouse-tracking is convenient because it is freely available and relatively easy to implement, it has the disadvantage of requiring visuomotor transformations from the horizontal plane (e.g., the table) to the cursor movements in the vertical space (i.e., the screen) (Gallivan & Chapman, 2014). On the contrary, recording hand movements in the three-dimensional space, for instance by using a series of infrared cameras that capture the location in space of reflective markers applied on the hand of participants (e.g., https://www.btsbioengineering.com/), would allow to study in a 1:1 fashion how reach-to-grasp/reach-to-touch movements that we commonly perform in our daily life are carried out in an experimental setting. In addition, since 3-D measurement of hand trajectories do not require the stimuli to be presented on a monitor, it allows to investigate movement parameters in a real-time interaction with objects (e.g., Betti, Zani, Guerra, Castiello, & Sartori, 2018) or between individuals (e.g., Sartori, Becchio, Bulgheroni, & Castiello, 2009), opening the door to the possibility of exploring how participants resolve online conflicts between their own and another person's beliefs in a ecologically valid scenario.

7.5 Conclusions

The current thesis has investigated whether and to what extent mindreading and motor processes are functionally related. Experiments 1A, Experiment 1B and Experiment 2 implemented an adaptation of the Buttelmann et al.'s interactive helping task and indicated that motor representations can be modulated by the beliefs of another person when task complexity allow to identify the relevant information. In Experiment 1A and Experiment 2 participants' anticipatory implicit behaviour (i.e., eye movements and postural leaning) foreshadowed the agent's belief-based action preparation while Experiment 1B did not reveal any indication of motor processing nor belief tracking, which I argued might have been due to the introduction of a layer of complexity in the task. Experiment 2 also provided some support to initial evidence suggesting that belief-tracking is impaired when the ability to motorically represent an action is disrupted. Experiment 3A and Experiment 3B tried to address the same questions with a task that did not involve helping an agent, but rather asked participants to move the mouse cursor to click the location of an object while an agent with an irrelevant belief spectated the scene. Contrary to the only published mouse-tracking experiment testing implicit mindreading, and regardless of a manipulation that I introduced in Experiment 3B to ensure that participants' attention was sustained throughout the duration of the trials, both studies revealed that trajectories were not more attracted towards the location where the agent believed the object to be located. Taken together, the data collected in real-time interaction and computer-based tasks using a combination of eye-tracking, postural leaning and mouse-tracking techniques provide support to the view that mindreading and motor processes are functionally related but it leaves it to future studies to advance our understanding on how to characterise the extent to which they are dependent from each other or one to another.

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Human ethics application approval 0000025609 (Psychology). Automated Email, Do Not Reply

RH researchmaster-help@vuw.ac.nz
To Jason Low
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Wed 29/11/2017 7:57 PM

Dear Dr Jason Low,

Thank you for your application for ethical approval (Adults' Tracking of Reaching Movements, reference 0000025609), which has now been considered by the Psychology Sub-Committee of the Human Ethics Committee.

Your application is approved as of today.
You may wish to check whether there are any new comments on your application. To do this, click on the Comments button (it looks like a speech bubble). If any particular page has comments, they will be marked with a flag on the left hand side of the screen. To access them, navigate to the desired page, and then click on the Page Comments button (it looks like a speech bubble with a page behind it).

Best wishes with the research.

Psychology Sub-Committee of the Human Ethics Committee

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