**When your beliefs guide my hands:** visibly constraining an agent modulates observers’ automatic belief tracking

**Contrasting freedom and constraint in order to uncover how belief tracking influences motor processes**

**Action Constraint of Others Modulate Automatic Belief Tracking in the Observer**

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Tracking what is likely to happen in dynamic social situations is inherently challenging, and – because observing others activates our own motor systems – one view is that motor representations facilitate action and social understanding. Converging evidence revealed through brain imaging, transcranial magnetic stimulation (TMS), and reaction times suggests that observation of an agent’s action leads to activation of a corresponding motor representation in the observer (as reviewed by Rizzolatti & Sinigaglia, 2016). Neuroimaging studies support that the observation of actions done by others triggers activity in the motor execution-related brain areas that includes the ventral premotor and inferior parietal cortices (Cattaneo & Rizzolatti, 2009; Rizzolatti, Fogassi & Gallese, 2009). Consistent with imaging data, studies applying magnetic stimulation to the motor cortex during observation of reach-to-grasp actions reveals increased excitability in those parts of the motor cortex that correspond to the observed movement. For example, when adults watch another individual grasp an object, motor evoked potentials triggered by the stimulation are elevated in the very same muscles that would be active if the observers were actually making that grasping action (Fadiga, Fogassi, Pavesi, & Rizzolatti, 1995; Urgesi, Moro, Candidi, & Aglioti, 2006). Most importantly for the present study, behavioural studies profiling reaction-time benefits on motor priming tasks indicate that movement observation (a task-irrelevant stimulus showing an agent lifting her index finger, for instance) can accelerate our execution of the same action and decelerate our execution of an incompatible action (Brass, Bekkering, Wohlschlager, & Prinz, 2000; Cracco, Bardi, Desmet, Genschow, Rigoni, De Coster, et al., 2018).

Notably, there can be different motor coding levels during action observation (Grafton & Hamilton, 2007; Rizzolatti & Sinigaglia, 2010; Sartori, Betti, Chinellato, & Castiello, 2015). Whilst some motor representations can map the low-level parameters that compose action (patterns of bodily configurations, joint displacements or muscle activations), others can selectively carry information relating to the goal of an agent’s action (i.e., the anticipated or observed outcomes to which another’s purposive behaviour is directed). There are TMS data indicating that motor representations code the goal of an agent’s tool-mediated behaviour and not necessarily the muscular pattern required to perform the movement, and that virtual lesions to the ventral premotor cortex impair judgments about the outcomes that bodily actions are directed to, but preserves judgements about which body parts are being observed (Cattaneo, Caruana, Jezzini, & Rizzolatti, 2009; Urgesi, Candidi, Ionta, & Aglioti, 2006). Likewise, when we witness an agent perform an action goal using a non-typical effector (kicking a ball with her finger or grasping a pencil with her foot, for instance), there is motor facilitation in the effector muscles that we typically use to achieve that action goal (i.e., the leg or the hand, respectively) (Betti, Castiello, & Sartori, 2015; Senna, Bolognini, & Maravita, 2014). Collectively, these findings suggest that goals of observed actions can be represented motorically in the observer (Rizzolatti & Sinigaglia, 2016; Rizzolatti, Fogassi & Gallese, 2001).

Tracking others’ behaviour involves being sensitive not just to an action itself but also to the context of an action. There is evidence suggesting that our motor system can identify the context in which specific actions are embedded. Iacoboni, Molnar-Szakacs, Gallese, Buccino, and Massiota (2005) monitored adults’ brain activity as participants watched three types of movies: clips of different background contexts (cup, teapot and plate of food arranged as if someone was about to have breakfast, or had finished); clips of a hand physically executing different grips (precision or whole-hand) to grasp a cup without context; and clips of a hand physically executing different grips to grasp a cup in the different contexts. The imaging data showed that the condition where participants witnessed grasping actions in embedded contexts, compared to the other conditions, elicited higher cortical motor activations. The results suggest motor representations can code more complex goal outcomes (grasp for drinking, grasp for putting away) of which the immediate action is a part.

Motor representations can carry information about the features of a situation even in the absence of any effective movement towards a target object. Costantini, Ambrosini, Tieri, Sinigaglia and Committeri (2010) required participants to execute a grip with either their left or right hand upon the presentation of a task-irrelevant go-signal (a virtual mug with its handle aligned to the left or right). The researchers found that elicitation of a spatial alignment effect—faster responding when the required hand to execute the motor act was compatible with the orientation of the mug handle—depended on the apparent possibility for participants to interact with the virtual object. The spatial alignment effect was elicited when the virtual mug appeared in near reachable space whereupon it could be apparently acted upon by participants. In a follow-up study, Costantini, Committeri and Sinigaglia (2011) found that a bystander’s space constraints for potential action could also modulate participants’ own motor behaviour; the spatial alignment effect occurred also when the mug was presented outside the reaching space of the participants but within the reaching space of a computer avatar. The findings suggest that motor activations can be deployed even without watching movements being actually performed, such that anticipating someone else’s potential action can excite planning and control of actions in the observer to influence task performance. It appears that the range of some motor representations can go far beyond merely mapping the kinematic features of movement: they can even enable tracking others’ potential actions given a certain situation.

If tracking the outcome-directedness of potential actions is an extension of motor processing, constraining an agent’s opportunity to act should significantly disrupt motor representations concerning another’s realm of agency. Liepelt, Ullsperger, Obst, Spengler, von Cramon and Brass (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. There was a marked slowing of participants’ reaction time in the condition where the observed agent’s corresponding index and middle fingers were tied to the table with metal clamps as compared to the conditions where the agent’s fingers were unrestrained or where the agent’s non-corresponding fingers (thumb and ring finger) were restrained. The results highlight that the physical body of an agent is constitutively relevant to certain kinds of cognition. The fact that another person’s restraint leads to a finger-specific slowing of reaction time in the observer, even when the restraint was response irrelevant, suggests that our motor system automatically takes on the task-relevant circumstances governing someone else’s potentially upcoming goal-directed action. Dovetailing with Liepelt et al.’s findings, Costantini et al. (2011) found that priming of participants’ own motor system to react more quickly (as demonstrated with the spatial alignment effect paradigm) was obliterated when the agent’s possibility to interact with an affording object was temporarily restricted (a transparent panel was placed between the computer avatar and the handled mug).

The available evidence that motor representations enables us to track the goals of others’ actions, although broad, does not entail that motor representations underpin the primary ways in which human beings engage in social cognition to play a role in the tracking of beliefs which specify someone’s reasons for action (Rizzolatti & Sinigaglia, 2010, p. 271). To make this bridge, our research experiment aims to test whether and, to what extent, visibly constraining an agent from potentially interacting with an object modulates observers’ abilities to automatically track that agent’s belief. Our experiment bears on two broader issues.

The first issue concerns how observers could ever distinguish between motor representations that are self-triggered and other-triggered. This issue arises given that witnessing someone else’s action leads to a direct activation of corresponding motor processes in the observer. The challenge can be acute. For example, patients with frontal lobe injury overly imitate someone else’s interfering finger movements that are not response relevant, and patients with Parkinson’s disease find it difficult to control automatic imitation of others’ postural instability as induced by motor contagion (Brass, Derfuss, Matthes-von Cramon, & von Cramon, 2003; Pelosin, Bisio, Pozzo, Lagravinese, Crisafulli, Marchese, et al., 2018). Neurotypical individuals, however, can enforce their own internally planned movement against an externally perceived movement. Bardi and Brass (2016) suggest that a deeper understanding of control of concurrently activated goal-directed motor representations may be gained by investigating its embedding in theory-of-mind (ToM) abilities. Consistent with this suggestion, studies show that there are overlapping brain activations when adults perform mentalising and motor-priming tasks (Spengler, von Cramon, & Brass, 2009). Moreover, training on a motor task that makes salient differences between the one’s own motor action and someone else’s motor action can transfer to improvements in spontaneously tracking another’s visual perspective on a ToM task (Santiesteban, White, Cook, Gilbert, Heyes, & Bird, 2012). This raises the question of whether impairing abilities to represent actions motorically might impair performance on a ToM task, which our experiment is designed to answer.

Second, in many social situations, successfully tracking an agent’s motor goal that specifies a target object also involves tracking the correctness of the agent’s belief about that object. Consider, for example, that Maxine is going to perform an action the goal of which is to grasp her ball. She falsely believes that her ball is in the right-side box, whereas actually it is inside the left-side box. If we ignore the Maxine's false belief, then fixing only upon grasping the ball as the goal of her action would generate the wrong expectation of how it would unfold—incorrectly predicting that she would reach to the left-side box to grasp her ball (Butterfill & Apperly, 2016). We need to track Maxine's belief in order to correctly identify the potential motor outcome of her action, which is that she would reach to the empty right-side box to grasp her ball. This creates a challenge for action observation: if we are to track how an agent’s action will potentially unfold, we cannot always rely on how things are but must also take her belief. Could the motor representations critical for tracking how the agent’s actions will potentially unfold also play a role in tracking her beliefs? No study, until now, has demonstrated that motor representations also matter for successfully tracking of an agent’s belief.

Bardi and Brass (2016) suggested that a functional connection between control of motor representations and belief tracking may be detectable in implicit ToM tasks “where participants’ performance depends on concurrent activations of different representations of the environment” (p. 162). We adopted Bardi and Brass’ suggestion by taking advantage of Kovacs and colleagues’ (2010) object-detection task, which yields a critical effect showing that adults’ rapid and automatic tracking of a bystander agent’s belief has an impact on observers’ own actions. The object-detection task involves adults observing a ball rolling behind a screen on a table and then rolling from behind the screen to off the table. The sequence also includes an agent who was present for some of the ball’s movements but not others and, consequently, could have a true or a false belief about the ball’s location. In the outcome phase, the screen falls away and participants must press a button as fast as possible if the ball is present. The task is considered to target automatic belief tracking because no reference is made to the agent’s belief about the ball’s location, and the agent does not perform any overt action when the screen is dropped. The critical finding, which we and many others have replicated, is that, compared to a baseline condition in which neither the participant nor agent expected the ball to be present (P-A-), participants are faster to respond when only the agent expected the ball to be present (P-A+), implying that the agent’s belief regarding the ball’s location is automatically encoded (Bardi, Six, & Brass, 2017; Bardi, Desmet, & Brass, 2018; Edwards & Low, 2019; El Kaddouri, Bardi, De Bremaeker, Brass, & Wiersema, 2019; Nijhof, Brass, Bardi, & Wiersema, 2016).

To test whether and to what extent visibly constraining an agent from potentially interacting with an object modulates observers’ abilities to automatically track that agent’s belief, we will compare whether participants’ susceptibility to another person’s belief is elicited when the agent is free to potentially act on the target and when the agent is constrained from potentially acting upon the target ……

Paragraph on our Predictions ….