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Reply to comment

The future of sensorimotor communication research Reply to comments on "The body talks: Sensorimotor communication and its brain and kinematic signatures"

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We are grateful to all the commentators, who raised several interesting points that enrich our analysis of sensorimotor communication (SMC) and help identify important directions for future research – which is particularly important, since the study of SMC is still in its infancy [1]. Here we discuss some of the most important theoretical issues and observations raised by Becchio and Panzeri [2]; Chater et al. [3]; Curioni and Sacheli [4]; Dockendorff et al. [5]; Era et al. [6]; Gambi and Pickering [7]; Green et al. [8]; and Ognibene et al. [9].

Becchio and Panzeri [2] offer a very interesting conceptualization of SMC in terms of information theory, and the "intersection information" between the information that can be coded (by a sender) and read out (by a received). This conceptualization leverages on ideas developed in computational neuroscience [10] and can greatly help us achieve a deeper understanding of SMC and develop novel analytical tools to study it during social interactions. More broadly, we strongly believe in the importance of developing formal theories of SMC. Some of us have indeed proposed a formalization of SMC [11] that appeals to similar principles as Becchio and Panzeri (e.g., that is important to consider both the "sender" and the "receiver's" sides when computing what is communicated), while focusing more on cognitive mechanisms (e.g., the "sender's" representation of the "receiver's" uncertainty) and optimality principles

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supporting SMC. Other, related formal approaches appeal to information theory to explain how humans may encode, communicate or hide intentions (e.g., current spatial goals or plans) during spatial navigation [12–15]. Developing in more detail these formal frameworks, as well as the idea of "intersection information", is an important research direction to improve our understanding of SMC.

Chater, Misyak, Ritchie, Watson, Griffiths, Xu and Mouzakitis [3] discuss a nice example of a complex, real-world situation in which SMC operates: driving. The example of car driving is particularly intriguing for theoretical reasons, as it permits to investigate both cooperative and competitive joint actions; and affords a variety of possible "communicative" actions beyond bodily actions (e.g., changes in speed and direction to communicate a desire, or a permission, to go first). Indeed, while most of the examples of SMC we offered in our review concern physical actions (because this is the domain where SMC has been studied so far), an important direction for the future is studying it also in relation to other kinds of actions, including actions mediated by artifacts like car driving or forms of stigmergy [16], [17]. The example of car driving is very important from a more practical perspective, too, given that autonomous vehicles are becoming a reality. We appreciate that the authors find strong links between our proposal on SMC with their idea that humans solve conflicts and negotiate agreements during social interactions using "virtual" forms of bargain that ultimately converge to the same results as a "real" bargain [18], [19]. Indeed, SMC may be the ideal way to support the (virtual and actual) bargains underlying human social coordination; and it can be used to find or modify agreements as well as to communicate (driving) intentions. We concur with the authors that this rich communicative dimension is immediately evident to humans and cannot be disregarded by technologies like autonomous vehicles. Failing to recognize that a car movement (e.g., decelerating) can have communicative intention (e.g., opening a gap for another car) can be disappointing or frustrating. All this makes driving an extremely interesting scenario for both improving our understanding of SMC and incorporating similar mechanisms in future technologies.

Curioni and Sacheli [4] stress the importance of understanding the neurobiological bases of SMC and in particular the (social) motor representations supporting it. We agree that important aspects of SMC can be understood within a "motor cognition" framework [20], in which joint actions are supported by motor representations that can be (in part or in toto) shared between co-actors [21–28]. While some of us have advanced specific computational proposals on how a putative neuro-cognitive architecture may support SMC [11] and related processes such as action and intention recognition [29], [30], many important questions remain open, such as whether and exactly how shared motor representations are engaged during SMC, and how they may interact with other neuro-cognitive and social processes (e.g., motivational processes to decide whether or not communication is worth; the prioritization of communication with in- or out-group members). In this respect, as highlighted in our review article on SMC [1], very few studies target directly the neural foundations and the engagement of (shared) motor representations in SMC. Understanding more deeply the neuro-cognitive processes supporting SMC may also help explain how it can fail, as in Curioni and Sacheli's example of individuals with autistic traits, who show reduced modulation of motor behavior – and more generally, a reduced ability to engage in successful social communicative behavior – during joint actions [31]. And perhaps it may also help us understand how to fix interactive failures [32], [33]. To add further to this, SMC may also be modulated by interpersonal (rather than merely individual) differences in social cognitive abilities and social relationship, which is often overlooked in joint action research. For example, it could be that previously affiliated interacting partners rely on more subtle forms of SMC, given that their joint coordinative behavior is more developed, and hence easier to predict. Hence, they may not need to modulate their motor behavior as much in order to achieve the joint goal, provided that they are mutually able to take their partner's perspective with more ease. Similarly, SMC may be more exaggerated by the growing asymmetry in two interacting partners' social cognitive abilities (provided that they are aware of this asymmetry) – as we see with mothers who over-emphasize their movements to aid their children in understanding their intention. The unexplored interpersonal asymmetry can be investigated along various dimensions: social cognitive abilities, social relationship, expertise, personality traits, social network position, etc. Even along low-level coordinative behavior, interpersonal differences can give insight into whether particular asymmetries (or symmetry) facilitate predictive mechanisms [34], and/or give rise to more mutually coordinative versus leader-follower behavior [35].

Dockendorff, Sebanz and Knoblich [5] highlight that any working definition of SMC should include the idea that communication is achieved by *intentionally deviating from the optimal, or the more efficient, action performance*. We are highly sympathetic to this view, which is a key point also in previous conceptual and computational works that attempted to model SMC during interactive behavior [11], [36]. Interestingly, as the authors suggest, focusing on deviations from optimality may help broadening the scope of SMC scenarios. While most current studies focus

on deviations from typical action kinematics or timing, there are other possible deviations that are interesting from a SMC angle, such as for example deviations from the most effective grasp type or action sequence – and the latter can be interesting to study SMC during sustained interactions over time or joint planning scenarios [37]. Furthermore, one can appeal to deviations from optimal higher-level expectations (as opposed to just from optimal low-level behavior) to link SMC and pragmatic theory of communication [38]. In this framework, speakers strive to provide relevant information during conversations, by minimizing their invested costs and maximizing the amount of information transferred to the listener (i.e., the maxim of relevance); much like "leaders" consider the costs and benefits of deviating from optimal behavior during most experiments studying SMC (see also [39] for a conceptual analysis of the "maxim of relevance" in terms of cost-benefit considerations). This parallel is intriguing and can help us to reconcile these disconnected fields as well as to design novel experiments that explore the parallels between SMC during linguistic and non-linguistic interactions. More broadly, an intriguing topic is how "violations of others' expectations" (about our own actions), which are apparently detrimental to interactive behavior of any kind, linguistic and non-linguistic, may instead serve fundamental communicative purposes.

Era, Boukarras, and Candidi [6] raise the very valid issue that the more sophisticated forms of SMC and their neural substrates, are often overlooked in interactive studies, which predominantly focus on more "minimal" forms of interpersonal interaction given their ease for experimental control. They propose that the underlying neural mechanisms that enable people to integrate one's own action with a partner's as well as monitor the joint outcome of this interaction, are crucial for understanding the neural processes that underlie SMC. Their perspective is very important in highlighting some of the studies that have added to the understanding of neural substrates supporting complementary interactions, mutual adaptation, and error monitoring [33], [40], [41], thus nicely extending our review. This is especially relevant because, as we have emphasized in our review, there is still a paucity of studies that study SMC – defined broadly – at neural levels. Their commentary also prompts the question of what future studies may be more appropriate to elucidate complex forms of SMC, beyond what we know from studies of minimal forms of interpersonal interaction. Intriguingly, despite their simplifications, the studies of "minimal interpersonal interaction" were able to capture quite sophisticated mechanisms that are putatively key also in more sophisticated forms of interpersonal interaction. For example, low-level interactions such as finger tapping have shown that successful interpersonal coordination is highly reliant on mutual adaptation (which in turn relies on error monitoring) and prediction [42]. Furthermore, mutual adaptation is crucial in both symmetric and asymmetric tasks (i.e. where partners have asymmetric task demands), where one's adaptability and flexibility in implicitly negotiating leader-follower roles with their partner facilitates coordination over non-adaptive regularity (such as with a completely predictable stimulus) [43]. Similarly, in tasks where online feedback is not available, simple tasks have shown that people overcome this asymmetry by integrating their partner's task with their own into their action-planning repertoire, and consequently adapt their own action to facilitate the joint goal [44]. What is still missing is a more thorough integration between studies employing more minimal versus more sophisticated motor interactions, and in particular an integrative theory that can satisfy different degrees and forms of SMC. In order to understand the neural mechanisms supporting SMC, we strongly believe that we need to build up on an integrative conceptual framework, which lays out the fundamental mechanisms including those that are not yet explored. Our review was a first step in this direction, but clearly a lot of theoretical, empirical, and computational work remains to be done.

Gambi and Pickering [7] stress that the distinction between SMC and linguistic communication is a matter of degree and not of kind. We agree that the many parallels that exist between linguistic and non-linguistic communication should not be disregarded; and in the review we have provided examples of SMC during linguistic exchanges (e.g., the motherese). In this regard, some of us have recently investigated the neural processes subtending mutual phonetic adaptation during "minimal" conversations [45]. However, our focus on non-linguistic interactions was motivated by the fact that linguistic interactions are by default considered to be communicative; whereas one goal of our review was to stress that also non-linguistic interactions can be communicative – not just in a weak sense (i.e., because some information is transmitted) but also in a strong sense, as exemplified by the fact that "leaders" can modulate their behavior in more or less informative ways, depending on context (e.g., joint goals or "follower's" knowledge). As the case to be made was about something non-communicative that (under certain conditions) may become communicative, this was more clearly exemplified by the fact that one can modify a "standard" pragmatic action (e.g., a physical, non-linguistic action) to achieve communicative goals; and that this can be done in a free-form way, as opposed to using a more conventionalized (linguistic or non-linguistic) code, while retaining the action's pragmatic objective (otherwise we should have included in our definition of SMC also pantomime and gestures like pointing). Yet the con-

cept of SMC is clearly applicable also in the context of linguistic exchanges, intended as "speech acts". As illustrated by the case of the motherese (and by many other examples by Grice [38], Austin [46], and Clark [47], and reported by Gambi and Pickering) language and dialogue can be understood within a broad pragmatic perspective – as forms of interactive behavior and joint action – in which communicative and pragmatic goals are combined. This perspective can be helpful for the design of novel experiments that identify more precisely SMC mechanisms within dialogues (or even within other forms of social communicative exchanges that exploit, for example, the internet). More broadly, it is worth noting that real world social interactions often involve a mixture of linguistic and non-linguistic exchanges, and in some cases one can use either "standard" pragmatic actions or speech acts in interchangeable ways to achieve the same goal. This prompts the question of which channels (linguistic and non-linguistic) are most exploited for SMC, in different contextual conditions. Besides advancing our understanding of SMC, addressing this kind of questions may also help design more advanced interactive technologies that communicate with us in linguistic and non-linguistic ways.

Green, McEllin and Michael [8] highlight that SMC can have a range of communicative (and meta-communicative) effects. They specifically focus on the proposal that SMC can (be used to) stabilize commitment during online interactions; for example, by (meta-) communicating that one is investing some effort in the interaction and is thus willing to persist, which may in turn prompt some reciprocation. Green, McEllin and Michael also suggest that forms of SMC that achieve different communicative or meta-communicative intentions, such as informing you about my action goal or about my commitment, may involve different signals. This idea is coherent with our proposal that SMC is flexible and even slightly different "messages" (e.g., I am going to grasp the cup to the right or to the left [11]) can imply quite different "signals"; and it prompts future studies that explicitly test specific differences between signals related to communicative or meta-communicative intentions. More broadly, an open question in the study of SMC is to what extent communicative (e.g., I signal to you that my goal is X) and meta-communicative (e.g., I signal to you that I am communicating my goal) dynamics are fused; whether and in which occasions it is possible to disentangle the former from the latter; and whether the addressees of SMC pick up on them or distinguish them. Communication theory, as developed in the context of linguistic interactions [48], clearly identifies a role for both communication and meta-communication; however, the extent to which this is also true in SMC remains to be fully established. As noticed in our review, whether or not "performers" and "observers" during SMC have, or recognize, meta-communicative intentions has not been fully established yet. It is possible that meta-cognitive functions of SMC are only implicit or cannot be fully (or easily) disentangled from pragmatic or communicative functions. On the other hand, it is possible that in some scenarios, it is sufficient that co-actors only engage in meta-communicative exchanges (e.g., they communicate that they want to interact effectively), perhaps for increasing their sense of commitment, without more specific communicative messages (e.g., without informing one another about the common pragmatic goal of an interaction). It remains to be fully established to what extent signals and meta-signals are present (or can be disentangled) during SMC; and the mechanisms by which they support interactive behaviors at large, including joint action success, tacit agreements, commitment etc.

Ognibene, Giglia, Marchegiani and Rudrauf [9] highlight the importance of considering both the "sender" (or "leader") and the "receiver" (or "follower") sides during sensorimotor interactions and SMC. We completely agree that a full comprehension of SMC (and of social exchanges more broadly) should focus on its truly interactive aspects, rather than just on one of the two sides – especially if one considers that in real world situations, the two sides or social roles often flip over time. In that respect, we notice that most of the current empirical studies that we discuss in our reviews have focused more on the "sender" than the "receiver" side. Yet as Ognibene, Giglia, Marchegiani and Rudrauf observe, there are several interesting aspects of receivers' behavior that deserve future investigations. For example, receivers may plausibly adopt "active" sensing and monitoring strategies to ensure that they can access the most relevant information from senders [29], [49], [50] – as opposed to being merely "passive" observers of his or her behavior. Another interesting set of open questions regards the cognitive requirements of receivers; for example, to what extent they need to recognize that senders have communicative intentions. As we discussed in our review, recognizing communicative intentions is considered to be key in communication theory [48]; but yet this topic has not been systematically analyzed in the context of SMC. As Ognibene, Giglia, Marchegiani and Rudrauf suggest, receivers can display a range of interactive behaviors, ranging from simpler (called "serendipitous") to more complex (called "engaged") in terms of cognitive requirements; and the extent to which these mechanisms are exploited during realistic interaction remains to be fully investigated.

In sum, we want to thank again our commentators for their stimulating ideas. We hope that their contribution will help broaden the scope of SMC theory and suggest novel interesting directions of research, to increase our understanding of SMC from theoretical, computational and empirical perspectives.

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