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Understanding how movement signals shape early social coordination and learning[☆]

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ABSTRACT

From early in life, social interactions rely on a rich exchange of nonverbal information. This review paper focuses on the nonverbal, kinematic information conveyed by how social partners move and proposes that such movement modulations may facilitate interpersonal coordination between infants and adults, as well as support infants' learning in early interactions. So far, findings on movement modulations have been investigated in isolation: sensorimotor communication in interpersonal coordination between adults (signaling) on the one hand, and in early teaching interactions between adults and infants (motionese) on the other. This paper integrates these findings and argues that both forms of movement-based communication operate along a continuum of predictability and surprise, which are flexibly adapted depending on the underlying social goal, i.e., interpersonal coordination or teaching. This leads to testable hypotheses on how predictability and surprise in adult movements could support infants' real-time action prediction and, consequently, their learning and optimization of interpersonal coordination, with a potential impact on social development in the long run. By integrating empirical findings from distinct research lines, the present review offers a novel framework to investigate how early social interactions and learning may be shaped by movement-based communication, opening new avenues for exploring developmental trajectories.

1. Introduction

The way we move encodes more information than can be attributed to the mere execution of instrumental actions alone (Becchio et al., 2024; Pezzulo et al., 2025). Movements can reveal our underlying emotions, intentions and, in some situations, can serve as communicative signals (Ansuini et al., 2014; Di Cesare et al., 2020; Pezzulo et al., 2019). In the context of social interactions between adults, interacting agents sometimes modulate their movements by implementing different forms of sensorimotor communication. The term refers to any instance where communicative signals are directly embedded into pragmatic actions. It occurs when an agent modifies the kinematic properties of a goal-directed action to systematically convey information to a partner, thereby facilitating smoother coordination and mutual understanding during interactive tasks, eventually increasing the chances of achieving a common goal (Candidi et al., 2015; Pezzulo et al., 2013; Sacheli et al., 2013; Vesper & Richardson, 2014). For example, if you are lifting a heavy box with a friend, you might exaggerate the slowing down of your movement (a kinematic deviation) to signal that you are about to set it down. This allows your partner to predict your intention and adjust their own motor response without the need for verbal instructions. But do movement modulations also play a role in interactions between adults and infants or young children? Particularly when interacting with preverbal infants, movement modulations have the potential of facilitating coordination, thus functioning as coordination tools. At an age at which interpersonal coordination starts to emerge, information

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conveyed by movement modulations could compensate for language or other conventional forms of communication, which are typically used among adults but are not to the same extent available in interactions with infants and young children.

Learning to coordinate their actions with others is integral to infants' early social development and contributes to social bonding with interaction partners (Meyer & Hunnius, 2020). Despite its potential, little is known about the role that adults' movement modulations play in supporting interpersonal coordination during infant-adult interactions. While movement-based communication directed at infants has been studied in various contexts, such as teaching (Brand et al., 2002; Meyer et al., 2023; van Schaik et al., 2020), questions remain. To what extent do adults alter the way they move to establish and maintain social interactions with infants? How sensitive are infants to these subtle movement changes? And how does interpersonal coordination benefit from their implementation?

To address these questions, we integrate previously isolated findings from research on sensorimotor communication in interpersonal coordination between adults (signaling) and findings on early teaching interactions between adults and infants (motionese). After reviewing and integrating these two lines of research, we will discuss how infants develop sensitivity to these movement changes and how this, in turn, may benefit their interpersonal coordination skills and their social development. We propose that, in both teaching and interpersonal coordination scenarios, adults may adjust their movement patterns to increase the surprise elicited by their behavior or enhance its predictability. These modulations may positively impact infants' learning: they facilitate the understanding of object functions in teaching (motionese) and improve the infants' ability to coordinate with others (signaling). This proposal, we argue, not only explains the distinct features and functions of movement modulations during early social interactions but also leads to testable hypotheses for future research.

2. Interpersonal coordination in early childhood

Early traces of interpersonal coordination are evident from the first days of life, when turn-taking begins to emerge in face-to-face interactions between infants and caregivers (Dominguez et al., 2016). By 2–3 months, infants engage in rhythmic interactions characterized by behavioral and physiological synchrony, for instance, in gaze behavior and vocalization (see Bell, 2020). Daily routines, including feeding and diaper changing, offer adults and infants opportunities to practice interpersonal coordination. Although these social interactions are initially largely scaffolded by adults, infants become increasingly active contributors to coordination success from early on (Fantasia et al., 2014, 2016; Reddy et al., 2013). Recent findings show that during the observation of an interaction, 9-month-old infants can infer whether two people coordinate rather than not (Begus et al., 2020), and 10-month-old infants can efficiently encode predictable features of social exchanges, such as the specificity of interpersonal action-reaction associations (Sacheli et al., 2023).

Research on interpersonal coordination in adults suggests that one of the most fundamental ingredients for successful coordination is the ability to predict the goal of an interaction partner and then, based on these predictions, adapt to their own movements in space and time (Sebanz & Knoblich, 2009). In a similar fashion, infants need to learn to plan and control their own actions as well as to predict and monitor others' actions as important skills for successful social interactions (Meyer & Hunnius, 2020). Research shows that, from about 6- to 9-months of age, infants are able to anticipate the goal of others' behavior based on the observation of their movement kinematics, for instance in actions like grasping an object (usually a toy) or grasping-and-placing (Daum & Gredebäck, 2011; Falck-Ytter et al., 2006; Kanakogi & Itakura, 2011; Natale et al., 2014; Quadrelli et al., 2019). It has been suggested that such predictions are enabled by agent-neutral motor representations that guide both one's action execution and action observation (Wolpert et al., 2003) and develop through visuomotor experience (Keysers & Gazzola, 2014; see, for instance, Colomer et al., 2023; Gerson & Woodward, 2014; Hunnius & Bekkering, 2014; Stapel et al., 2015, 2016).

Thus, around their first birthday, infants are well equipped with one key requirement for successful coordination in joint action, namely the capacity to predict other people's actions. From their second year, young children become more proactive and display more interactive coordination behaviors, important to joint actions. Between two and three years, children become less error-prone and more stable in their planned coordination when acting in turns with adults and peers (Brownell, 2011; see for instance Endedijk et al., 2015). At age four, children master more complex interactions and accommodate their actions more flexibly to others (Meyer et al., 2016). Still, in their first two to three years of life, infant-adult interpersonal coordination is far from the levels of accuracy and smoothness reached in adult-adult interactions.

Apart from its key role in facilitating the achievement of joint goals, coordination also supports social bonding. Specifically, proficient interpersonal coordination has been linked to positive social effects such as positive affiliation and prosocial behavior. After moving in a temporally coordinated fashion with another person, infants (Cirelli et al., 2014) and young children (Kirschner & Tomasello, 2010; Tunçgenç & Cohen, 2018) were shown to demonstrate more helping behaviors. Thus, being involved in joint activities provides infants not only with opportunities to learn how to execute joint actions, but also potentially supports the foundations for social bonding with other people.

Given the importance of interpersonal coordination in social development, it becomes crucial to identify the factors that play a role in establishing and maintaining successful and smooth interpersonal coordination with infants. Below, we will review research on sensorimotor communication. This form of communication has been found in interactions among adults, serving to support smooth coordination. We then discuss how this compares to movement modulations in infant-directed actions, and what role such sensorimotor communication may play in promoting successful adult-infant interpersonal coordination.

3. Movement modulations in interpersonal coordination between adults

While in many social interactions people rely on language to facilitate the achievement of joint goals (Bahrami et al., 2012; Clark, 1996), other interactions (e.g., when moving a heavy object together, Sebanz et al., 2006) need to be performed at such speed or with such accuracy that language falls short in its role of "coordination smoother" (Vesper et al., 2010). In certain scenarios, spoken language is either too slow (e.g., during team sport competition), not functional (e.g., in noisy environments), or simply not available (e.g., when talking is not allowed or possible, as in musical performance or when interacting with a non-verbal interaction partner). When faced with these challenges, co-actors can improve their coordination for instance by modulating their instrumental actions in a communicative way, thereby adding a communicative goal on top of their merely instrumental goals (Pezzulo et al., 2013, 2019). These modulations in movements are referred to as ***signaling*** (Pezzulo et al., 2013; Sacheli et al., 2013).

Previous findings suggest that this form of sensorimotor communication is flexible in that it is tailored to the specific demands of the interaction. For instance, actors implement specific kinematic modulations depending on the perceptual access of their co-actors (Vesper et al., 2016; Vesper & Richardson, 2014). Modulations are then shown to facilitate the predictions of the partners' actions (Vesper & Richardson, 2014) and, subsequently, the preparation of a proper response by the predicting partner (Pezzulo et al., 2013, 2019). To illustrate, research has also shown that when people need to synchronize by reaching an object at the same time, co- actors tend to emphasize the wrist trajectory and grip aperture of their reaching movements (Sacheli et al., 2013). By doing this, they not only reach for the object but also inform the interaction partner about their upcoming action, allowing the latter to more easily disambiguate the target of the upcoming reaching movement. This, ultimately, facilitates the co-actor's prediction and movement response, thus leading to better coordination (see also, Candidi et al., 2015). Interestingly, adults change the temporal dynamics of their movements on a virtual gameboard when intending to communicate about a goal location in the absence of verbal communication, and this signaling behavior is enhanced when they believe to interact with a child, while the interaction partner is in fact another adult unbeknownst to the participant (Newman-Norlund et al., 2009). This provides an indication that signaling may also occur in child-adult interactions.

As indicated above, one core feature of signaling is that the movements used to signal deviate from typical patterns present when executing an instrumental action (Pezzulo et al., 2013). Such deviations imply a tradeoff between individual cost in terms of energy expenditure and social benefits in terms of joint action success (see Donnarumma et al., 2017, for a proposed model of the cost-benefit scheme sustaining signaling implementation). Signaling can thus be conceptualized as a deviation from optimal action performance, embedded with a communicative meaning (Dockendorff et al., 2019; Pezzulo et al., 2013; Vesper et al., 2017), serving the function of facilitating coordination. Since it implies a deviation from optimal action performance, it appears to be implemented only when necessary – and then reduced when no longer required (Candidi et al., 2015), although agents may sometimes choose to continue performing signaling to maintain the overall functionality of the communication system (see Schmitz et al., 2018). Notably, while this section mainly focuses on deviations in spatial movement features, signaling can be flexibly implemented by modulations of temporal features as well, depending on the task and environmental constraints (Vesper et al., 2017).

Accordingly, signaling is particularly useful in coordination settings in which there is an **asymmetric distribution of information** between co-actors. This is the case when one co-actor (the leader/sender) knows the actions to perform to achieve a joint goal, while the other, a naïve agent (the follower/receiver), either does not have knowledge about the action or does not have the same perceptual access to it. One prototypical example is pair dancing, where the leader modulates her dancing actions, thus guiding the follower via exaggerated hand pressure and other bodily signals.

Infant-adult interactions share several of the features found in asymmetric interactions between adults, like asymmetries in knowledge (e.g., knowing the rules of a game), perceptual access, and skills. Moreover, relying on language might be limited when infants are still pre-verbal. It remains, however, unclear whether and how signaling plays a role in interpersonal coordination between adults and infants.

4. Movement modulations in teaching interactions between adults and infants

While, so far, no study has directly looked at movement modulations for the purposes of facilitating coordination in adult-infant interactions, developmental research demonstrates that adults alter the kinematics of their movements in early teaching interactions. Movement modulations in this context have been referred to as ***motionese*** (Brand et al., 2002) or infant-directed actions (van Schaik et al., 2020). These kinematic modulations occur spontaneously during episodes of communicative demonstration in which adults teach infants about a range of behaviors, from action types (e.g., stacking cups; Rohlfing et al., 2006) and action boundaries (e.g., the shaking or pressing components of object-directed actions; Brand et al., 2013) to unfamiliar object functions (Brand et al., 2002; Koterba & Iverson, 2009; Williamson & Brand, 2014) and their identity (Hirai et al., 2022). Often, these modulations are preceded or produced in tandem with other attention-getting behaviors (Csibra, 2010), such as eye contact (Fukuyama & Myowa-Yamakoshi, 2013), facial expressions (Koterba & Iverson, 2009), or speech (Hirai et al., 2022; Schreiner et al., 2020). As such, motionese takes place in a highly interactive context during which parents engage the attention of their infant, for instance, by exchanging objects back and forth throughout the teaching episode (van Schaik et al., 2020) and adapt their demonstrations to the attentional state and the motor skills of the learner (Fukuyama et al., 2015).

Importantly, a prerequisite for infants to potentially benefit from the communicative signals embedded in their interaction partner's movements is that they are able to perceptually detect modulations from typical movements and to attribute meaning to such modulations. Previous literature on action observation in infancy provides some indication regarding these two abilities (Addabbo et al., 2020; Schröer et al., 2022; Skerry et al., 2013). For instance, 3-month-old infants appear to be already sensitive to the way grasping actions are typically performed and to be able to detect deviations (often referred to as "inefficient" actions; Skerry et al., 2013). The ability to detect similar deviations also enables one-year-old infants to recognize others' emotions (happiness or anger) embedded in movement modulations of transporting actions (Addabbo et al., 2020; Schröer et al., 2022). Research on motionese suggests that it is the detection of such deviations that attracts infants' attention and promotes learning (Hirai et al., 2022).

Indeed, in various teaching contexts, specific kinematic modulations introduced by adult demonstrators were observed, including changes in movement amplitude, velocity, and trajectory, as well as repetitions, punctuation, and overall simplification in the execution of movements (Brand et al., 2002; van Schaik et al., 2020). Some of these modulations appear to be action-specific while other modulations are evident across different types of actions (van Schaik et al., 2020). For instance, parents move faster when demonstrating how to elicit a rattling sound of an object by shaking, while they move slower in demonstrating how to turn on a light switch. In contrast, independently of the action-type, parents repeated demonstrations more often, performed the actions in closer proximity, and demonstrated action-effects for longer, when interacting with their infant than with other adults (van Schaik et al., 2020).

The prevalence and spontaneity of such infant-directed modulations of behavior have led some to argue that motionese might be the expression of a more general tendency to tailor communicative behaviors to support infants' learning: adults and teachers would do so by segmenting a rich, multimodal stream of information into discrete, meaningful units (Hilton et al., 2021; van Schaik et al., 2020). From this perspective, motionese allows infants to extract the function (or goal) underlying a movement and different components of the complex movements they see (Brand et al., 2007, 2009). Similarly, such a segmentation process has been found in speech ("motherese", e.g., Dominey & Dodane, 2004; Golinkoff et al., 2015) and gestures (Grimminger et al., 2010; Iverson et al., 1999). Interestingly, research on pretense play also shows that caregivers modulate their behavior to communicate that children are engaged in a symbolic game and signify that their actions are not to be intended as serious gestures: in these instances, caregivers look at infants more and use prolonged and exaggerated movements with a communicative intention (see Tamis-LeMonda & Lockman, 2020, for an overview on parents' roles in scaffolding infants' play).

A question that follows from this is whether infants benefit from such modulations. Recent research suggests that they do (Hirai et al., 2022; Meyer et al., 2023). Action modulations lead infants and toddlers to imitate the observed actions more often (Fukuyama et al., 2015; Fukuyama & Myowa-Yamakoshi, 2013; Williamson & Brand, 2014). As early as 4 months of age, infants more easily encode the identity of the demonstrated objects when shown with motionese (Hirai et al., 2022). At 6–8 months, motionese draws infants' attention more than adult-directed actions as evident in their looking behavior (Brand & Shallcross, 2008). A motionese-induced modulation of infants' attention is also evident in neural processing (Meyer et al., 2023), which was found to predict the infants' subsequent success in performing the demonstrated action. Also, 8- to 10-month-old infants are more likely to engage in exploratory behavior after seeing a demonstration using motionese (Koterba & Iverson, 2009). Together, these findings indicate that movement modulations as found in motionese support learning by not only enhancing infants' attention to the demonstration but also affecting their subsequent behavior with novel objects and facilitating the acquisition of novel actions.

To summarize, motionese research shows that adults spontaneously modulate the kinematics of their actions when interacting with infants during episodes of teaching and demonstration and that these modulations help infants in (action) learning. However, it remains unclear **how this translates to a facilitatory role in interpersonal coordination** and how these findings relate to findings on signaling in adults. Are movement modulations during motionese and signaling similar or based on different functions and processes? Do adults modify their actions in interaction with infants also outside of teaching contexts, when trying to improve interpersonal coordination? Would signaling facilitate infants' online action coordination and benefit their social development in the long term?

In the following, we address these questions by systematically analyzing the similarities and differences between the kinematic modulations found in social learning contexts of infant-caregiver interactions (motionese) and those described in coordination tasks involving two adults (signaling).

5. Comparing movement modulations when coordinating and teaching

Movement modulations in interpersonal coordination between adults (signaling) and in teaching contexts with infants (motionese) are both forms of movement-based communication. Below we will discuss the similarities and differences between motionese and signaling to inform concrete hypotheses on the role of movement modulations in early coordination between infants and adults.

5.1. Similarities in kinematic modulations between signaling and motionese

These include modulations of movement amplitude (*signaling*, Vesper & Richardson, 2014; *motionese*, Koterba & Iverson, 2009), velocity (*signaling*, McEllin, Knoblich, & Sebanz, 2018; *motionese*, van Schaik et al., 2020) and increased action-effect durations (*signaling*, Vesper et al., 2017; *motionese*, van Schaik et al., 2020). Other kinematic features, like exaggerations in grip aperture and wrist height, have only been reported in studies on *signaling* (Candidi et al., 2015; Sacheli et al., 2013), while repetitions and more general features like engagement and body orientation have only been studied in the context of *motionese* (Hirai et al., 2022, van Schaik & Dominici, 2020), although it remains to be tested whether these features are in fact not modulated in the other social context or has simply not yet been explored. Furthermore, in both motionese and signaling, there is some evidence that agents can flexibly adapt to the specific competences and needs of their partner: for example, adults may modulate the spatial and/or temporal movement features that are more relevant to the task at hand (in *signaling*, Vesper et al., 2016), or they may adapt demonstrations to the attentional state and motor skills of the learner (in *motionese*, Fukuyama et al., 2015).

Experimental evidence also indicates that the sender's signaling is sensitive to the performance achieved in past interactions (Candidi et al., 2015), and that motionese takes place in a bidirectional exchange where the child's attention is monitored and used to adapt kinematic behavior on-line (Fukuyama et al., 2015; Pitsch et al., 2014). This indicates that in both signaling and motionese the sender can adapt the signal to the needs of the receiver. Motionese and signaling are also adaptable to situational constraints, such as the specific action to perform or the object involved in the task.

5.2. Differences in kinematic modulations between signaling and motionese

Perhaps the two most critical and consequential distinctions between signaling and motionese regard: (i) the distinct social contexts in which they are implemented, and, relatedly, (ii) the different role that (spatial and temporal) movement variability plays in these two contexts.

About the social contexts in which signaling and motionese are implemented, they crucially differ in their **underlying goals**, namely, coordinating with another person in the case of signaling and teaching another person in the case of motionese. Thus, while motionese is used by adults to draw their infant's attention to something (e.g., how objects are manipulated) with the aim of transferring some knowledge (e.g. the object function), signaling is mostly used to improve interpersonal coordination by facilitating the prediction of actions and disambiguating between action alternatives (Candidi et al., 2015; Sacheli et al., 2013; Vesper et al., 2016), with the aim of achieving an instrumental goal (e.g., moving together a heavy object in the right direction; in the case of adult-infant interactions, we can think of changing the diaper, feeding the infant, playing with the ball).

The similarities and differences in modulations of movement kinematics aimed at teaching vs. coordinating are also highlighted by two recent studies on adult-adult interactions (McEllin, Knoblich, & Sebanz, 2018; McEllin, Sebanz, & Knoblich, 2018). In one study, adult participants were instructed to either synchronize a sequence of movements with a partner (coordinating) or to teach that same movement sequence to a naïve learner (teaching). In both situations, participants increased the amplitude of their movements. However, only when they had to synchronize with their partner did adults decrease the velocity of their movements, which was argued to facilitate interpersonal coordination in the time domain (McEllin, Knoblich, & Sebanz, 2018). A second study used point-light animations of these movements and asked observers to infer the social goal of the actor, i.e., either synchronizing with or teaching the movement sequence to someone else. The authors found that observers reliably used modulations in amplitude and velocity as a cue to infer the social goal (McEllin, Sebanz, & Knoblich, 2018; see also Trujillo et al., 2018; Strachan et al., 2021; Tominaga et al., 2022). These results support the hypothesis that, despite several commonalities, the difference in kinematic modulations between signaling and motionese may depend on the underlying social goal (interpersonal coordination vs. teaching) and the specific task demands derived from such goals.

One way in which these different goals are implemented is via the modulation of **movement variability**. In certain joint actions, movement variability is reduced trial by trial to improve predictability and support coordination (Vesper et al., 2011, 2017); this led to suggest that "making oneself predictable" (Vesper et al., 2011) can be considered as an effective "coordination smoother" (Vesper et al., 2010). When combined with an exaggeration of movement trajectory (see Sacheli et al., 2013; Vesper et al., 2017), a reduction in movement variability may contribute to an improvement in the signal-to-noise ratio, making the sender's action even more easily interpretable by the observer. On the contrary, trial-by-trial movement variability is enhanced to support generalization and learning in teaching interactions (Meyer et al., 2023), suggesting that the two phenomena clearly diverge in this regard.

In what follows, we will argue that, despite these differences in social goals and in the amount of movement variability in their implementation, the same underlying processes may sustain and reinforce the implementation of movement modulations during adult-infant interactions, in both coordination and teaching contexts.

6. Common underlying processes: the role of predictability and surprise

As illustrated in Fig. 1, we suggest that viewing movement modulations through the lens of *predictability and surprise* may help reduce the kinematic modulations of signaling and motionese to a common

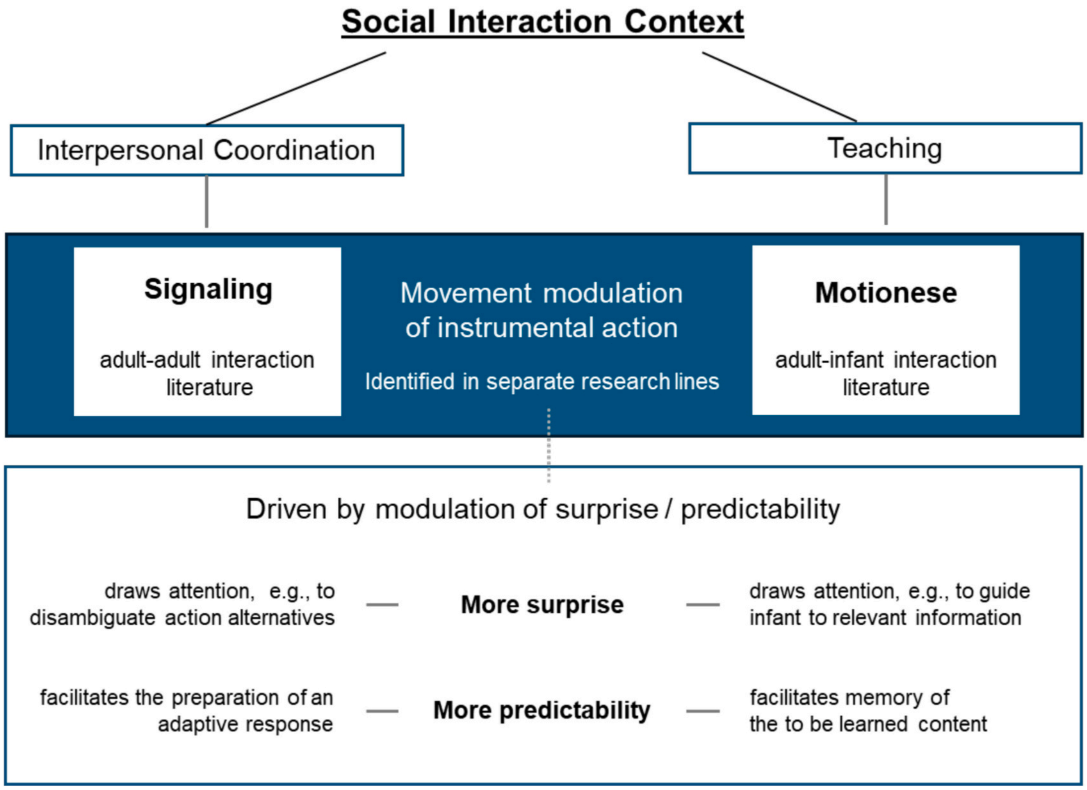

Fig. 1. The figure illustrates the similarities and differences between the communicative movement modulations that have been studied in the context of interpersonal coordination between adults (signaling) and early teaching interactions between adults and infants (motionese). As discussed in the main text, we argue that both forms of movement modulations operate along a continuum of predictability and surprise, which are flexibly adapted depending on the underlying social goal, i.e. interpersonal coordination or teaching.

denominator, especially in social exchanges that are repeated over time between the same partners, as often occurs in child-caregiver interactions.

6.1. Why predictability and surprise?

Predictability and surprise offered by the environment are key components of the general principles of information processing, attention, and learning. That is, prominent unifying accounts of cognition suggest that we build predictive models of the world, which we continuously update by comparing our model predictions with sensory input from our environment (Clark, 2013; Friston, 2010; Ward et al., 2025). Predictability in the environment, as reflected in patterns and regularities, plays an important role in learning. Research shows that newborns can already detect statistical regularities in the environment and build predictive models of the world based on them (Hunnius, 2022; Saffran & Kirkham, 2018; see, for instance, Bulf et al., 2011). Information that deviates from one's internal model predictions, so information that offers surprise, is found to draw attention and is used to update models to improve future predictions (Den Ouden et al., 2012; Hunnius, 2022; Kayhan et al., 2019; Stahl & Feigenson, 2015). Infants actively shape their learning through exploration (Twomey & Westermann, 2018; Raz & Saxe, 2020); they are guided by attentional biases that lead them to new and relevant "surprising" input and determine very rapid generalization (Gerken et al., 2015). Importantly, we here define surprise as the prediction error experienced by the perceiver when the environmental input deviates from the perceiver's prior internal model, that is, when a violation of expectations occurs. Therefore, surprising stimuli capture attention precisely because they offer an opportunity for gaining information and updating internal models.

As illustrated in Fig. 1, we propose that predictability and surprise play an important role in movement modulations of instrumental actions in the context of both coordination and teaching:

- Coordination. Signaling implementation implies deviations from the optimal movement trajectory. These deviations are surprising because they differ from the infants' model of how that movement is normally performed. They thus attract the infant's attention and help disambiguating between action alternatives. Over repeated interactions, deviations from movement optimality are coupled with a reduction of movement variability. Due to this repetition, such signals facilitate the infants' predictions about what the partner is doing and what response is expected. This facilitation supports infants' learning of interpersonal coordination.
- Teaching. In a teaching context, motionese leverages initial surprise to orient the learner's focus toward the information-rich parts of the action. Thus, adults use surprising movements to draw infants' attention to the content that is being taught and thereby facilitate the processing and memorization of the demonstrated action. Additionally, more predictable movements during these demonstrations (after the infant's attention has been caught) may allow for better pattern detection and learning.

Several studies on movement modulations in interpersonal coordination and teaching contexts are coherent with this proposal as discussed in the following.

6.2. Predictability and surprise in movements during interpersonal coordination

As suggested above, signaling depends on the combination of an exaggerated trajectory and a reduction in movement variability (Sacheli et al., 2013; Vesper et al., 2017), which makes the sender's action more predictable by the observer.

The function of **predictability** in movements for interpersonal coordination is shown by a study by Vesper and collaborators (Vesper et al., 2016). In this task, adult participants were instructed to touch a target location at the same point in time, starting their movements from different positions. When visual access to the other person's movements was limited and adults could only rely on auditory feedback indicating when the other reached the target area, adults reduced their movement timing variability, making their action timing more predictable. Consistent with previous results (Vesper et al., 2011), this was found to positively relate to interpersonal coordination performance. The close link between increasing movement predictability during interpersonal coordination and the ability to predict someone else's actions is also evident in early childhood. A study with 2½-year-old toddlers shows that toddlers who reduce their movement variability more during interpersonal coordination with an adult are also better at making temporal predictions of another person's actions as illustrated by anticipatory gaze (Meyer et al., 2015). Similarly, a study involving adults participants showed that the better the participants' action prediction abilities the stronger their tendency to take into account the partner's task during joint action (Sacheli et al., 2022).

Regarding the potential role of **surprise** in movement kinematics for action coordination, some evidence comes from research on target disambiguation in coordination tasks. Sacheli et al. (2013) showed that adults exaggerate the wrist trajectory when signaling which target location their interaction partner should synchronously reach toward (Sacheli et al., 2013). A follow-up study also showed that agents shape their signaling taking into account the story of past interactions, increasing/reducing it depending on the pair past performance (Candidi et al., 2015). From the sender's perspective, making movements more surprising by deviating from typical performance can be functional in disambiguating between action alternatives (see also, Pezzulo et al., 2013; Donnarumma et al., 2017). This facilitates the task of the receiver, who has to infer the other's motor intentions and action goals, both when these are proximal and distal (Dockendorff et al., 2023), and use this information to react accordingly.

6.3. Predictability and surprise in movements during teaching

Findings of a recent EEG study with infants (Meyer et al., 2023) corroborate the role of **surprise** in movements modulations in a teaching context. In this study, brain activity of 15-month-old infants was measured while they watched videos of someone demonstrating the same sequence of actions repeatedly (e.g., stacking five rings, one after another, on a peg). In different action sequences, the movement amplitude was manipulated, thus generating three experimental conditions: while in the "normal" condition the model moved by following a natural movement amplitude, in the "high" condition the trajectory was amplified, and in the "variable" condition high and normal movement amplitudes were combined within the same action sequence. The findings show that, compared to the other conditions, the "variable" one elicited a stronger frontal theta response in infants, which was associated with more attention. This stronger processing also correlated with subsequent learning of the demonstrated action and with more explorative behavior on the objects used during the demonstration. Computational modeling additionally showed that this effect was likely driven by surprise (here quantified as Shannon information) introduced in this condition. In line with this, a study by Fukuyama et al. (2015) suggests that caregivers introduce more surprise in their movements as reflected in increased movement variability to engage their infants' attention. In a teaching task between infants and caregivers, they found that caregivers increase their movement variability when their infant does not show signs of learning the demonstrated action and decrease their movement variability when infants successfully performed the demonstrated actions. Less is known about the role of making instrumental actions more predictable in teaching contexts. Still, evidence for **predictability** in parental behavior being related to infants' statistical learning (Forest et al., 2025) points toward a potential role of predictability in movement modulations also in a teaching context.

7. A research agenda to explore the role of signaling in interpersonal coordination between infants and adults: two working hypotheses

This leads us to the following testable hypotheses regarding the role of movement modulations in infant-adult interactions, assuming the adult is the sender and the infant is the receiver of signals conveyed through movement modulations.

Hypothesis 1. (*(Adults)*) If adults modify their movements when interacting with infants and young children analogously to what they do with adults, we expect them to perform more predictable movements in time and space when the interpersonal coordination requires high temporal and spatial precision, and more surprising movements when the interpersonal coordination requires disambiguating between (action/target) alternatives; the implementation of signaling should also reduce when the interactive exchange becomes over-learned and communication is redundant;

Hypothesis 2. (*(Infants)*) If detected by infants, we expect these modulations to lead to better action prediction (i.e., more precise predictions in space and time) and more accurate disambiguation of action alternatives during the interaction; together, this implies a better basis for infants' appropriate response in the interaction, ultimately resulting in better interpersonal coordination.

Lastly, as mentioned in Section 2 (Interpersonal coordination in early childhood), coordination quality (smoothness and efficiency in achieving coordination success) is closely linked to positive affiliation and prosocial behavior (Kirschner & Tomasello, 2010; Tunçgenç & Cohen, 2018). In line with this, recent evidence in adults has shown (McEllin & Michael, 2022) that detecting signaling in their partner's movements is used by adults as a cue to infer the other's effort investment in the interaction, which in turn fosters the participant's trust and generosity toward the partner. The emergence of smoother coordination with their caregivers through signaling may therefore lead to enhanced social bonding between the infant and the caregiver. Practicing interpersonal coordination and learning to better coordinate with others over time may then also set the stage for better coordination with peers and build the foundation for positive social bonds. Importantly, within this light, communicative motor exchanges must be seen as bidirectional. The communicativeness of the adult and the responsiveness of the infant are likely interconnected, influencing one another in various functional - or, potentially, maladaptive - ways. Future research is needed to address whether movement signaling in social interactions benefits infants' interpersonal coordination skills and their broader social skills set later in life.

One promising way to systematically address these hypotheses in future research is through combining empirical developmental research with computational modeling and advances in quantifying communicative signals from naturalistic movements (Becchio et al., 2024; Hunnius & Meyer, 2025; Schröder & Gredebäck, 2025). Novel tools that automatically extract movement kinematics like DeepLabCut (Mathis et al., 2018) or OpenPose (Cao et al., 2019) in combination with recent kinematic coding frameworks that allow identifying informative signals in movements and the encoding thereof (Becchio et al., 2024) are particularly promising in this respect. This approach may allow us to quantify predictability and/or surprise in movement modulations (for instance, see Meyer et al., 2023) during infant-adult interactions and to link these to the coordination performance.

8. Conclusion and open questions

In this paper, we examined the role of communicative signals embedded in movements for social coordination between infants and adults. As direct empirical evidence remains missing, we reviewed findings on sensorimotor communication in adult interactions (signaling) and on movement modulations in early teaching interactions (motionese). We propose that both signaling and motionese rely on introducing predictability and surprise in goal-directed actions (see Fig. 1). Accordingly, we proposed testable hypotheses for infancy research on interpersonal coordination. Together, this lays the foundation for the next steps in systematic investigation on the role of signaling in social coordination between infants and adults.

If adults use communicative signals embedded in movements to facilitate coordination with infants, continuous interactions with adult partners may offer promising training grounds for infants to develop action predictions and interpersonal (coordination) skills. On the contrary, the absence of sensorimotor communication signals in early infant-caregiver exchanges may constitute a behavioral marker of less optimal interaction trajectories, e.g., in the context of suboptimal infant-caregiver relationships or in neurodevelopmental disorders that alter the infant's coordination abilities, such as autism spectrum or developmental coordination disorders (see, for reviews, Cerullo et al., 2021; Xavier et al., 2016). Looking at individual differences in adults' use of signaling and how they relate to adults' social functioning (see Curioni et al., 2017; Curioni & Sacheli, 2019) would also be of interest for infants' development.

Several additional open questions remain. For instance, are there any longer-term benefits of signaling in interpersonal coordination for infants' later social development, for their interaction skills, or social bonds with others? Future studies of communicative signals embedded in movements during infant-adult interactions may provide valuable insights into these questions. Finally, one might ask when children themselves begin to modulate their own movement patterns with a communicative intent to facilitate social interactions. Interestingly, it has been shown that 5-year-old children change their communicative behavior depending on whether they believe they are interacting with another child or a toddler, and that this tendency is modulated by the child's social experience (Stolk et al., 2013). This evidence lays the groundwork for future research, suggesting that children may also start being able to strategically and flexibly use movement modulations with communicative intent by the end of the preschool age.

CRediT authorship contribution statement

Lucia Maria Sacheli: Writing – original draft, Validation, Methodology, Investigation, Conceptualization. **Martin Dockendorff:** Writing – original draft, Investigation, Conceptualization. **Marlene Meyer:** Writing – review & editing, Conceptualization. **Arianna Curioni:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

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None of the co-authors of this paper have financial or other conflict of interest.

Data availability

No data was used for the research described in the article.

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