**An Interactionist Perspective on the Development of
Coordinated Social Attention**

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Abstract

Infants' ability to coordinate their attention with other people develops profoundly across the first year of life. Mainly based on experimental research focusing on infants' behavior under highly controlled conditions, developmental milestones were identified and explained in the past by prominent theories in terms of the onset of specific cognitive skills. In contrast to this approach, recent longitudinal research challenges this perspective with findings suggesting that social attention develops continuously with a gradual refinement of skills. Informed by these findings, we argue for an interactionist and dynamical systems view that bases observable advances in infant social attention skills on increasingly fine-tuned mutual adjustments in the caregiver infant dyad, resulting in gradually improving mutual prediction. We present evidence for this view from recent studies leveraging new technologies which afford the opportunity to dynamically track social interactions in real-time. These new technically-sophisticated studies offer unprecedented insights into the dynamic processes of infant-caregiver social attention. It is now possible to track in much greater detail fluctuations over time with regard to object-directed attention as well as social attention and how these processes relate to one another. Encouraged by these initial results and new insights from this interactionist developmental social neuroscience approach, we conclude with a 'call to action' in which we advocate for more ecologically valid paradigms for studying social attention as a dynamic and bi-directional process.

Key words: Social attention, predictive processing, mutual engagement, reciprocal interaction, dynamical systems, eye tracking, hyperscanning

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I. Introduction

Humans are social creatures from birth and devote a great deal of time attending to faces, bodies, and actions throughout their lives. Of course, this is not surprising given that social attention and interpreting others' actions are foundational to how we communicate, learn about the social and physical world, regulate emotions, and develop attachments with others. By adulthood and most likely long before, we are all experts in our social understanding of other people. The central question that we ask in this chapter is how social attention develops and how it relates to social understanding.

In this chapter, we define social attention as a dynamic process involving the selection and interpretation of biological motions, such as gaze cueing, pointing, facial expressions, head and body orientation, and goal-directed actions as well as other social cues involving speech and prosody, smell, and touch. Critically, social attention is not just a product of development, but it is a process as well. Infants enter the world seeking social information, which is important not only for its survival value, but also because it enables social interactions and social learning (Schultz et al., 2015). By directing attention toward the social world, infants gain increasing experience with their caregivers and other people with whom they interact. Initially, this experience is limited to reflexively seeking social stimulation drawn from the sights, sounds, and smells of their caregivers (e.g. Bartocci et al., 2000; Bushnell, 2001; DeCasper & Fifer, 1980), but, in turn, caregivers and others respond contingently to this attention (Bigelow & Power, 2014; E. Z. Tronick, 1989). Over time, this information seeking by infants evolves into social interactions involving mutual and reciprocal behaviors that are dynamically coordinated between individuals (Gallagher, 2013).

Early on, infants' actions while socially interacting are highly variable, but are gradually shaped by the feedback they receive from their social partners. Through repeated cycles of selecting and then responding to social stimuli, infants' responses to social information become more finely attuned with experience. For example, infants become increasingly sensitive to multimodal sources of social information specifying contingent vs. non-contingent responses (Smith & Gasser, 2005). Such experiences explain why successful adaptation to the social environment leads to new and more advanced social behaviors that are mediated by the brain. In turn, behavior exerts powerful influences on the development of neural systems by selecting inputs that dynamically modulate neural activity, thereby shaping brain structure and function (Byrge et al., 2014). As such, this perspective represents an epigenetic view of development that offers a valuable framework for evaluating the contributions of social attention not only during infancy but later in life as well.

The key significance of this framework is that it focuses on the *function of social attention* rather than merely on the development of this construct. Currently, there is a voluminous literature on the development of social attention, especially with regard to faces and eyes (e.g., Bertenthal & Boyer, 2015; Salley & Colombo, 2016). Yet, there is little known about how and why it develops. Some theorists suggest that social attention is primarily innate (e.g. Baron-Cohen, 1995), but this view does not satisfyingly explain the substantial changes that continue to occur during the first year as the infant progresses from seeking social stimuli to dyadic and finally triadic interactions (Hoehl & Striano, 2015). The research literature also demonstrates that responses to social cues vary among individuals and even within an individual across time. Moreover, many other factors, such as social cognition or state or emotion regulation contribute to inter-individual variability, and thus make it extremely challenging to

observe systematic changes across individuals (Rothbart & Derryberry, 1981). These complex interactions illustrate that social behavior cannot be fully investigated within a deterministic and stationary model of human development, although this is currently the common state of affairs.

Although we acknowledge that the study of social attention encompasses different models and methods, virtually all posit that behavior can be analyzed by decomposing the problem space into static variables or systems that are linearly related to each other. Currently, most of the research focuses on infants' responses to a social cue, such as gaze direction or facial expression, but much less is known about how and when infants begin to dynamically interact with a social partner. One reason for the sparseness of relevant findings is that most studies focus on a single individual, the infant. Oftentimes, infants are presented social stimuli from a third-person perspective, such that they are tested for their observation and representation of a social stimulus, but not for their interaction with that stimulus (Boyer et al., 2020). This type of paradigm obviates the need for infants choosing between different stimulus cues. For example, infants are presented with a sequence of events, such as an actor eliciting an infant's attention, and then looking or pointing in a specific direction, followed by an object appearing either in that direction or the opposite direction; infants merely have to attend to the stimuli in the order they appear and not choose when and what to look at (e.g., Bertenthal et al., 2014; Gredebäck et al., 2010; Senju & Csibra, 2008). Moreover, the person with whom the infant interacts is following a pre-recorded script that may or may not be responsive to the infants' behaviors. Furthermore, this person is simply repeating the same stereotypical behavior over a series of trials. As a consequence, researchers are measuring infants' responses to a specific social cue and then they generalize infants' responses to continuous and ongoing social interactions (Schilbach et al., 2013).

We contend that the prototypical paradigm for studying infants' social attention is insufficient for explaining how it develops. Consider, for example, the simple act of looking at someone else's eyes. The act of looking cannot explain why this occurs, especially when looking at a real person, because looking serves a dual function. On the one hand, it is designed to acquire information from the individual who is the focus of attention, while, on the other hand, it is signaling information about the motives and intentions of the looker (Nasiopoulos et al., 2015). These behaviors will mutually influence each other and dynamically change over time. As such, infants will construct an understanding of these social cues from the multifarious experiences that they engage in with others.

In more naturalistic situations, such as an infant interacting with a caregiver in a cluttered room amongst a set of objects over an extended period, the caregiver might alternate between looking at the child and the objects and jointly playing with those objects or showing them to the child. The caregiver will also be communicating with the infant via her facial expressions, vocalizations, and a host of other cues. The question then becomes, how much will infants' social attention be guided by the actions of the social partner, such as eye gaze, gestures and goal-directed actions, the orientation of her face, her body posture, or changes in her object-directed actions? This is a critical question because infants' systematic selection of social information in triadic interactions may not only precede but catalyze their appreciation of shared intentions or common ground (Boyer et al., 2020; Mundy & Newell, 2007). In other words, these preferences establish new opportunities for social interaction and social learning, which might very well contribute to infants' social understanding.

The key point here is that in order to understand how social attention contributes to social understanding, we must go beyond assessing infants' understanding of different social

cues in dyadic and triadic interactions. It is not enough to study infants' responses to social cues, such as faces or eyes, because these studies focus on what infants know, but not how they know the meaning of this information. Social knowledge derives from the repeated actions by infants and the responses by the social partners. It is therefore necessary to place emphasis on social interaction rather than social attention, per se. These interactions involve a mutually engaged and co-regulated coupling between infant and caregiver such that they mutually affect each other (Gallagher, 2013). As such, meaning is derived from neither the perspective of the infant or the caregiver, but rather is a construction of the mutual and co-regulated coupling between the two subjects. This emphasis on a second-person perspective is beginning to receive serious attention in the developmental literature (Hoehl & Markova, 2018; Reddy, 2003; Schilbach et al., 2013), but there is still much work to be done if this perspective is to deliver on its promise of explaining how social understanding develops.

In the remainder of this chapter, we will attempt to flesh out the ideas that we have outlined above. In section II, we will begin by discussing what contributes to learning and development. In particular, we will discuss how predictive processing and corrections from errors will result in a more adaptive understanding of the social and physical worlds. The next section (section III) will briefly review what we have learned about social attention from a third-person perspective (i.e., measuring infants' responses when they observe other people acting or communicating), and then highlight some of the theoretical limitations of this approach. In section IV, we will address the need for real-time process-oriented research to explain how social interaction is the engine for the development of infants' social understanding. Examples of this research involving eye tracking and hyperscanning studies will be discussed. Lastly, section V

will highlight emerging themes and future directions as we continue to benefit from new technologies to study the development of social attention and social understanding.

II. Development of social attention through the lens of predictive processing

II.1. Learning in response to prediction errors. When learning how to navigate their complex social and physical environment, infants constantly have to adjust their mental representations of the world, of other people and of themselves in order to become more and more proficient social agents. Predictive processing (PP) has become a prominent theory in the cognitive neurosciences (Clark, 2013) and provides a useful framework for understanding learning in early human development (Köster et al., 2020). According to the PP account, the brain does not passively receive and process sensory input. Instead, the brain constantly forms predictions about upcoming inputs and events and dynamically updates internal predictive models based on sensory information (Friston, 2005, 2010). These generative models exist at every level of the neural hierarchy from basic sensory and motor regions to networks engaged in higher-order reasoning and complex problem solving. Furthermore, these models are not rigid, but dynamically adapted based on incoming information, which serves to successively minimize prediction errors in the long run. These generative models are not deterministic, but rather probabilistic and based on the extraction of statistical regularities in the sensory input that the organism encounters. Two principal types of inferences are employed whenever a prediction errors occurs: (1) *active inference*, that is adjusting the world according to internal models through action and/ or (2) *perceptual inference*, that is adjusting internal models of the world according to new sensory information (notably, these notions of active and perceptual inference resemble Piaget's concepts of assimilation and accommodation, respectively; Piaget, 1952).

To give a simple example of an everyday situation, an infant may want to grab a toy offered to her by her older sister. Shortly before reaching the toy, the older sister retracts her hand and puts the toy out of reach again. The infant, having expected to be handed the toy from her sibling, will now experience a prediction error and may update her mental model of the ongoing interaction through perceptual inference. She may, for instance, look into her older sister's face and spot a mischievous smile, indicating that her sister is not helping her to get the toy at all, but rather teasing her (Striano & Vaish, 2006). Alternatively, the infant may now, depending on her motor and communication skills, through active inference, try to change the interaction back to a give-me-the-toy situation, by protesting loudly or by grabbing the toy out of her older sister's hand.

As argued previously (Köster et al., 2020), it is exactly these kinds of situations inducing prediction error, in the developmental literature often termed *violation of expectation*, that offer important learning opportunities for infants (Stahl & Feigenson, 2015). Perceptual inference, in particular, allows infants to generate better, more useful models of the world. In the physical domain this is reflected, for instance, in infants' highly effective learning about the hidden properties of objects that behave in unexpected ways, such as seemingly defying gravity (Stahl & Feigenson, 2015). Köster and colleagues (2020) suggest that infants are motivated to minimize prediction errors in the long run, inducing them to seek out information specifically about objects that behave in an unpredicted manner and to update their mental models of the world accordingly. They argue that predictive processing is a general learning mechanism, which applies widely to different domains from learning about the physical world to infants' motor learning as well as their social learning (see next section). Human infants possess near endless curiosity and drive to learn and they readily leave their comfort zones in order to explore, for

instance when standing up trying to walk after just having mastered crawling or crawling up and down inclined surfaces after just having learned to crawl (Adolph et al., 1997). According to PP accounts of infant learning, infants are motivated to generate predictive models that allow them to act on and move through the world in increasingly apt ways in the long run, instead of relying permanently on sub-optimal solutions that they acquired early on (Kayhan & Kwisthout, 2017; Köster et al., 2020). Thus, infants would not be content with acquiring one way of locomotion that affords only a limited view of the surroundings, such as crawling (Hoch et al., 2020; Kretch et al., 2014). Instead, they would continue to explore and acquire new action possibilities, for example walking, even though transitions between different ways of solving a problem usually entail particularly high degrees of uncertainty. In other words, infants learn to move, but they just as much move in order to learn (Adolph, 2008).

II.2. Implications of predictive processing for social learning. How can the PP framework be applied to the development of social attention and social understanding? Social interactions afford infants with manifold learning opportunities, gradually helping the infant to resolve uncertainties, to generate better-adapted models and to derive more and more accurate predictions from these models that allow them to act in increasingly proficient ways. There are at least two relevant facets of social learning that are probably tightly entwined, but often researched independently from each other. First, the infant learns about the *physical world* through others. Provided that an infant repeatedly learns from or with the same person, for example a caregiver or a sibling, this will likely result in more and more mutually aligned representations of the world and increasing common ground between infant and caregiver. Second, the infant learns about the *social world*, that is about other people, their intentions and perspectives, as well as their mutual relationship.

To give an example, learning about the physical world entails learning about the emotional valence and potential dangers of objects as operationalized in classic social referencing paradigms. In these studies, infants around their first birthday are typically exposed to an unfamiliar, often ambiguous object, such as a toy robot (Gunnar & Stone, 1984; Hornik et al., 1987; Klinnert et al., 1986; Moses et al., 2001; Mumme et al., 1996). Infants will orient toward adults (their caregivers or an experimenter) when encountering such an ambiguous object, that is they actively seek information about something they are not yet able to mentally represent or whose behavior they cannot reliably predict. Infants then usually adjust their behavior toward the object according to the emotional signals they receive from adults: They are more inclined to approach and touch the objects after receiving encouraging, positive expressions from the adult than when the adult expresses a negative emotion such as fear, disgust or anger.

Interestingly, several studies report that infants are more susceptible to adults' emotional signals when encountering ambiguous (i.e. unpredictable, objects or situations) rather than clearly aversive or potentially dangerous objects or situations (Campos et al., 2003; Gunnar & Stone, 1984). This observation is in line with the notion that infants seek out additional information especially when their mental models of the world do not yet afford them reliable predictions (Köster et al., 2020). Repeatedly learning about the world from or with particular others, such as caregivers or siblings, will likely lead to more overlapping mental models and predictions among these individuals. These could be manifested at the level of dyads or small groups as more similar neural responses to the same stimulation (Parkinson et al., 2018, see further discussion below) and at the level of cultural groups as more similar ways of perceiving and acting on the world (Nisbett & Masuda, 2003).

Learning about the social world from and with other people entails, for instance, making better predictions about others' actions based on their inferred goals or mental states. For example, 12-month-old infants seem to take into account the efficiency of a simple action, such as turning on a touch-sensitive light, and they will reenact an inefficient action (using the head instead of the hand) specifically only when they cannot make out a rational reason for the inefficient action, for example the hands were occupied (Gergely et al., 2002). Consistent with the view that infants experience a prediction error when observing such an inefficient head-touch action, one of us, and colleagues, recently found an increased neural Nc response, associated with increased attentional orienting. In addition, there was an N400-like component response, associated with detecting semantic violations, when one-year-old infants observed a head-touch as opposed to a hand-touch action (Langeloh et al., 2020). Furthermore, infants showed higher neural motor activation for the observation of unexpected head-touch compared to expected hand-touch actions, suggesting updating of their action predictions in motor regions of the brain (Langeloh et al., 2018).

In sum, we can imagine a myriad of ways in which such social learning affects social coordination at the level of dyads, larger groups or even cultures. In particular, achieving an instrumental goal using an inefficient action strategy has been associated with learning about social behavioral norms and rituals (Kenward et al., 2011; Keupp et al., 2013; Legare & Nielsen, 2015; Wen et al., 2016). It seems plausible that quickly learning and conforming to the behavioral norms established in a group renders individuals' actions more mutually predictable, thus minimizing prediction errors and enabling smoother social exchanges within the group (Veissiere et al., 2019).

Crucially, neither social learning about the physical nor about the social world are unidirectional exchanges; instead, social interactions are fundamentally bidirectional (Beebe & Steele, 2013; Cohn & Tronick, 1988). Thus, as the infant learns about the physical and social world through the caregiver, the caregiver's representations of the world will most likely also be affected by the exchanges with the infant. Crucially, the caregiver will also learn about the infant and will improve predicting the infants' needs and actions (Fotopoulou & Tsakiris, 2017). Tracking and understanding these dynamic and bidirectional processes requires taking a *second-person* perspective (Schilbach et al., 2013) on early social interactions (Hoehl & Markova, 2018; Reddy, 2003). Here, the infant is studied as an active participant in mutual and reciprocal exchanges with social partners. The dyad is the unit of observation rather than the individual. From this view, it is insufficient to record infants' behaviors and brain responses in experimental paradigms where the infant is merely an observer to someone else acting or communicating (so-called *third-person* approach).

We should strive to better understand how dynamical, reciprocal exchanges unfold and lead to changes in the generative models of the infant as well as the caregiver. Recent neuroscience research in adults has demonstrated that friends respond with more similar brain activity patterns to the same audio-visual stimuli than strangers (Parkinson et al., 2018). Furthermore, shared understanding of narratives goes hand in hand with more similar neural responses across individuals (Nguyen et al., 2019). Simply put, closely affiliated adults perceive the world more similarly. Yet, it is currently unknown how these patterns of brain activity come about and whether they rely on shared experiences. People may seek out as friends other people with similar ways of seeing the world. Keeping in mind, however, that completely accurate and objective mental representations of the world are impossible to achieve based on incomplete and

messy sensory input, it is unlikely that merely idiosyncratic individual learning experiences shape the way people respond to the world. It seems much more likely that social learning, starting in early development, plays an important role and leads to the co-creation of shared representations across infants and their caregivers and later their peers and friends. In this view, social learning leads to more or less similar models of the world and thus more or less similar patterns of responding and acting on the world across people depending on the quality and frequency of their shared experiences.

In the next section, we outline briefly what we have learned about the early development of social attention from traditional research on how infants perceive and respond to social signals from a third-person perspective before highlighting the limitations of these conventional approaches. We will discuss why, in our view, social attention should be studied as a bidirectional process of mutual prediction and inference in order to gain deeper insights into the mechanisms through which infants become increasingly proficient social agents and come to co-create shared representations of the world with their caregivers and other people.

III. A brief review of current findings and theories of social attention

III.1. Empirical research from a first- or third-person perspective. Research into the perceptual preferences of newborn human infants has consistently demonstrated their preference for looking at faces with open eyes (Batki et al., 2000) and direct gaze (Farroni et al., 2002, 2005). Along with perceptual biases toward faces in general (Johnson et al., 1991), biological motion (Simion et al., 2008), and voices (Vouloumanos et al., 2010), this preference ensures that the infant will preferentially orient toward other people. This ensures that in a normal environment, with caregivers around, the infant will receive ample sensory input of faces,

biological motion and speech, kicking off a process of *interactive specialization* of brain regions involved in the processing of social information (Blasi et al., 2011; de Haan et al., 2003; Johnson, 2000; Johnson et al., 2005). Interactive specialization refers to a probabilistic epigenetic process in which brain regions are functionally specialized through the interaction of the organism with the environment and the coordination of brain activities across neural networks. For instance, a brain region initially responding to a range of visual objects will be gradually tuned to the processing of upright human faces and specifically faces belonging to the race and ethnicity infants encountered most frequently. Evidence for this theory comes from, among other sources, electrophysiological research into the development and fine-tuning of face-specific brain responses (de Haan et al., 2003). By contrast, reduced early orienting towards social stimuli, and faces in particular, is associated with a lack of neural specialization in individuals with Autism Spectrum Disorder (Johnson et al., 2005).

As reviewed extensively elsewhere (Hoehl et al., 2009; Hoehl & Striano, 2015), research on infants' behavior and neural processes as a spectator (third-person perspective) of social information has shown that across the first two years after birth, infants become increasingly more accurate in detecting the targets of other people's head and gaze direction. Starting out from attention cueing effects in computerized paradigms (Farroni et al., 2004; Hoehl et al., 2008; Hood et al., 1998; Reid & Striano, 2005), infants become increasingly able to follow others' attention direction toward referents across greater spatial distances (Butterworth, 1998; D'Entremont et al., 1997), behind occluders (Csibra & Volein, 2008; Moll & Tomasello, 2004) and behind themselves (Deak et al., 2000). Infants also seem to develop an understanding that open eyes are needed for seeing (and consequently stop following adults with closed eyes) around the end of the first year (Meltzoff & Brooks, 2007). At this point, infants also start to

actively engage others in sharing visual experiences by pointing toward interesting events (Liszkowski et al., 2004) and checking back with the social partner to determine whether both are actually paying attention to the same thing (Carpenter et al., 1998). Thus, beyond merely following the attention direction of others, infants at this point are able to engage in more sophisticated forms of shared attention (Siposova & Carpenter, 2019), displaying evidence of being aware that they are sharing experiences with their social partners. Here it is useful to distinguish between *responding to joint attention*, including following gaze and pointing on the one hand, and *initiating joint attention*, that is actively pointing and sharing attention on the other hand, both of which have been linked to differentiable neural processes and functional brain networks (Mundy et al., 2000; Mundy & Jarrold, 2010).

This extensive empirical research offers multiple insights into how social attention develops across the first few years. By focusing, however, on the infant instead of the dyad as a system and adopting a first- or third-person view, we argue that findings from this line of research are incomplete, and primarily descriptive rather than explanatory (see also, de Barbaro et al., 2013). In particular, we now know very well when in development infants typically acquire certain social attention skills, but we do not really know how or why they show this developmental progress.

III.2. Illustrative theories for explaining the development of social attention. One prominent theoretical account posits that infants acquire a concept of *seeing* and of other people possessing their own visual perspectives through a so-called “like me” mechanism (Meltzoff, 2007; Meltzoff & Brooks, 2007, 2008). According to this view, infants link their own first-person experiences with their visual environment to others’ visual experiences, which the infant can only track from a third-person perspective. Thus, based on their own experiences with closure or

occlusion of eyes, the infant learns to infer that someone else with closed or occluded eyes cannot visually perceive a potential referent in the environment and they stop following this person's head direction accordingly. Meltzoff and Brooks (2008) demonstrated in an elegant experiment that personal experience with eye occlusion through a blindfold facilitated infants' understanding of eye occlusion and decreased their gaze following behavior of another blindfolded person. While convincingly making the point that infants are able to learn through linking their own first-hand experiences with the experiences they observe from a third-person perspective in others, this account does not explain how and why infants reach the developmental milestone of understanding eyes as instrumental for seeing by around 12- to 18-months of age. Moreover, it remains unclear why infants apparently do not learn about seeing from opening and closing their own eyes before the age of 12 months.

Tomasello and Carpenter (2007) offer another influential theoretical account aimed at explaining why infants seem to shift in their behavior from merely following the attention cues of others early in the first year to checking back with them and actively engaging them in episodes of shared attention, for example through pointing, around one year of age. According to the "shared intentionality" account, infants start to recognize other people as intentional agents with different experiences, perspectives, and goals of their own around the end of the first year. In a similar vein, it was suggested that infants around 9 months of age develop *secondary intersubjectivity*, meaning that they acquire the new capacity to represent triadic (person-person-object) relations (Trevarthen & Aitken, 2001; Trevarthen & Hubley, 1978). These accounts, however, leave open the question of how and why such a major shift in infants' perception of and reasoning about their social partners and their relations comes about at exactly this age. More importantly, this view has been criticized on the basis of empirical data consistently

showing a gradual development of social attention skills across the first year (de Barbaro et al., 2013; Deák, Krasno, Jasso, & Triesch, 2018; Lavelli & Fogel, 2005; Striano et al., 2007), rather than a sudden shift at some particular age.

III.3. Social attention develops continuously and involves improving mutual prediction

Empirical evidence collected in longitudinal studies on social attention in naturalistic interactions paints a clear picture of continuous development in infancy (de Barbaro et al., 2013; Striano et al., 2007), or perhaps an overlapping waves model (Lavelli & Fogel, 2005), rather than a stage model based on cross-sectional experimental data such as reviewed in the previous two sections. For instance, Lavelli and Fogel (2005) observed mother-infant face-to-face interactions in families' homes weekly between birth and 14 weeks of age. They report a gradual increase of infants' facial expressions co-occurring with gaze at mothers' face, thus providing evidence for increasingly active and emotionally positive forms of attention toward the mother across the first three months.

A second study was conducted longitudinally at 4, 6, 9, and 12 months of age and consisted of a micro-analysis of triadic interactions involving infant, mother, and objects (de Barbaro et al., 2013). The authors report several important observations consistent with gradually increasing sophistication of sensory-motor coordination between infant and mother across the first year. Starting out from shared interest in dyadic exchanges and mutual focus of attention on objects offered by the mother, dyads gradually increase the number of loci of attention. They engage in increasingly complex turn-taking exchanges and they develop routines, for example giving an object back and forth. Note that mutual routines, in particular, depend on recurring action patterns and require accurate mutual prediction to work. An important takeaway from this

study is that age-related changes in the observed dyads resulted from a process of *mutual adaptation* with mothers showing adaptive scaffolding accounting for infants' growing abilities on the one hand, and infants developing increasingly sophisticated social attention skills benefitting from the opportunities offered by their mothers on the other hand. In a follow-up study, the authors observed the gradual development of more flexible decoupling of visual attention and manual object exploration (e.g. infants were able to watch the mother manipulating an object while keeping manual contact with another object themselves), as an important precursor to interpersonal turn-taking activities (de Barbaro et al., 2016). This observation is in line with research showing that *interpersonal* eye-hand coupling (i.e. visual attention to the interaction partner's object manipulations) goes along with higher levels of joint visual attention as well as more frequent mutual switches of visual attention in one-year-old infants and their caregivers (Yu & Smith, 2013, 2017).

Further evidence for continuous development of social attention comes from a longitudinal study on infants' social attention skills using standardized tasks in weekly lab visits between 7 and 10 months of age (Striano et al., 2007). The authors reported that a range of social attention skills, including gaze following, point following and coordinated attention, develop gradually over this period of observation. Furthermore, very similar to previous studies (Carpenter et al., 1998; Slaughter & McConnell, 2003), the authors found little evidence for systematic correlations between the different skills that were measured. This failure to find significant correlations argues against the notion that a single cognitive construct, such as the emergence of shared intentionality by the end of the first year (Tomasello & Carpenter, 2007), underlies the development of social attention. The predictive processing (PP) perspective, in contrast, would not necessarily predict that infants who are accurate gaze followers are also

equally accurate at point following or pointing. This is because infants might well form different patterns and routines of communication with their caregivers, some perhaps regularly interacting with avid pointers, others with caregivers who engage more often in eye contact and gaze following. Depending on the interaction patterns enacted in the *dyad*, infants will develop some skills more (quickly) than others. Consistent with this view regarding individual differences, a recent study indicated that differences in infants' experiences with their caregivers account for a substantial amount of variance in infant gaze-following behavior (Astor et al., 2020).

IV. Studying social behavior at finer spatial and temporal scales

IV.1. Time scales of human behavior. One of the key implications of our review thus far is that the study of social attention benefits from observing infants and young children in naturalistic social interactions. Much of what we have learned from these studies is based on careful observation of the interaction between infants and caregivers. These observational studies are important, but do not provide an opportunity for drilling down into the finer spatial and temporal details of these dynamic interactions. If we are to more fully understand the processes by which social attention contributes to social understanding then we need to study this phenomenon as a dynamical system.

By definition, a dynamical system is high-dimensional, multi-level and multi-causal, and nonlinear (Bertenthal, 2007; Thelen & Smith, 2008). What has been lacking in existing studies is a way of modeling how behavior is dynamic and multi-causal and especially how it unfolds over multiple time scales. Why is so little attention devoted to the dynamics of behavior? Our sense is that the temporal dimension is often obscured by the time scale at which a behavior is studied. For example, we think of social behaviors as learned over an extended period of time,

but once acquired, these behaviors function automatically in a seemingly fixed way. Of course, these behaviors are all dynamically assembled each time they are executed, but the assembly often takes place at a faster time scale than our sampling rate. If, for example, we are measuring social interaction at a sampling rate of once per second, then faster processes, such as eye movements or neural responses, will be excluded from the explanatory process. It is thus essential to consider in our modeling that human behaviors operate at multiple time scales, and that these time scales are hierarchically related.

An excellent framework for thinking about the relation between these time scales was proposed by Alan Newell (Newell, 1990). In this framework, intelligent systems are built up from multiple levels of systems in hierarchical fashion (see Table 1). Each system is a collection of elements or components that are linked together and interact, thus producing behavior. As one moves up the hierarchy of system levels, component size increases and speed decreases. Expansion occurs in time as well. Thus, each level of processing is hierarchically related to the previous level in terms of simpler operations combining and producing a more complex operation at a slower time scale than that occurring at the previous level.

Until recently, it was not possible to study social interactions at faster time scales than permitted by observational studies. This situation began to shift in the past decade with the advent of new technologies and new paradigms. In this section, we review some of these advances involving eye tracking and neural processing. These measures are embedded in paradigms involving real or at least perceived social interactions, and typically each participant's actions affect the other and vice versa. The key feature of these studies is that real-time communication occurs in such a way that participants experience mutual engagement with their partners (Redcay & Schilbach, 2019).

IV.2. Eye tracking during social interaction. The springboard for studying social interaction with eye tracking was the advent of mobile eye tracking in which infants were fitted with a head-mounted eye tracker (Franchak et al., 2011). These eye trackers recorded the head-centered visual scene as well as participants' gaze sampled at 30 or 60 Hz. Unlike remote eye trackers that required infants to remain stationary and look at a screen, infants were now capable of freely exploring their environment. By now, these head mounted eye trackers have been used successfully in a number of labs testing infants (e.g., Bambach et al., 2013; Chen et al., 2020; Pérez-Edgar et al., 2020).

Yu and Smith (2013) were the first to capitalize on this technology for studying joint attention between infants and caregivers. One-year-old infants and their caregivers were fitted with remote eye trackers while they played with two sets of three toys for two minutes per set. Each of the toys as well as the faces of the infants and caregivers were defined as areas of interest (AOIs) in order to determine where participants looked. By recording the sequential distribution of gaze samples to the AOIs, Yu and Smith could measure how much visual attention was distributed to each other's faces as well as to the actions on the objects.

On each trial infants and caregivers could alternately look at a hand holding a toy or the other's face. As such, this situation was very different from the prototypical remote eye tracking study since infants could not only look at their caregiver's face or manual actions, but also act on the toys in the scene themselves. The results revealed that infants devoted most of their looking to their caregivers' or their own hands acting on objects and not to their caregiver's face (see Deák et al., 2014 for a similar finding without eye tracking). These findings were noteworthy because they challenged the conventional view that joint attention was primarily achieved through gaze following (Brooks & Meltzoff, 2005; Carpenter et al., 1998). This was clearly not

true when infants and caregivers were studied in a situation in which they were both capable of moving and manipulating objects. Apparently, there are multiple pathways or definitions for specifying joint attention (Siposova & Carpenter, 2019), and coordinating attention to actions on objects will sometimes trump gaze following, because the actions are highly salient and are likely to recruit attention independent of gaze cues by the social partner (Bertenthal et al., 2014; Deák et al., 2018; Yu & Smith, 2013).

These initial findings by Yu and Smith (2013) were extended in a follow-up study (Yu & Smith, 2017) revealing that joint attention to the hand actions of one participant were determined not only by how often infants and caregivers looked at the same object at the same time, but also by the visual and manual behaviors that preceded joint attention. There were multiple pathways leading to the same outcome suggesting that joint attention is softly assembled in response to contextual and task cues. Also, the likelihood of different pathways occurring changed between 12 and 18 months of age with parents' handling of objects decreasing and children's handling increasing. This latter finding is consistent with other gaze cueing results suggesting that children become increasingly the initiators of joint attention during this period (Mundy & Newell, 2007). As such, some of the developmental trends with regard to joint attention are similar regardless of whether attention is directed toward the eyes or toward manual actions.

Although the findings from head-mounted eye tracking have significantly contributed to our understanding of joint attention, the mechanisms responsible for why and how infants and toddlers follow hands-and-objects more than eye gaze still need to be explicated. Yu and Smith (2013; 2016) suggest that hands are larger and more salient than eyes, and therefore infants' gaze is more likely to be recruited by the hands. Moreover, eye-gaze direction is spatially less precise than a pointing or reaching hand, which may also contribute to young children's bias to follow

hands and not eye-direction. Although this explanation has some merit, it is not completely convincing because it is often the eyes and head in combination, and not just the eyes that direct the observer's gaze in naturalistic situations. This movement coupled with the high contrast of the iris against the sclera of the eye (Emery, 2000), causes us to question the assertion that eye-head direction is not sufficiently salient. Furthermore, it is well established that actions on objects are visually guided, and thus necessitate that participants look at the target of their reach or their manipulation of an object (e.g., Flanagan & Johansson, 2003). Moreover, related research reveals that both adults and infants will often predictively follow the goal-directed actions of their social partner (e.g., Flanagan & Johansson, 2003; Gredebäck & Falck-Ytter, 2015; Monroy et al., 2020). These goal-directed actions are continuously changing, and thus recruiting infants' visual attention for greater periods of time than gaze direction.

Just to be clear, we are not challenging the finding that infants and mothers look more at hands-and-objects than at faces, but rather the explanation. Our analysis of the infant-caregiver interaction is that the information about the infant's or caregiver's gaze direction can be ascertained very quickly, whereas the information about the caregiver's or child's actions on the toys is continuously changing and therefore both the child and parent are more motivated to look longer at the hands-and-objects. Thus, infants and caregivers will follow the actions of hands on toys for much longer than the actions of eye gaze and head direction, but this is not to suggest that eye and head direction is ignored during these triadic interactions. In order to evaluate this conjecture more systematically, it is necessary to drill down further into the visual processing that occurs during these play episodes.

In spite of the greater precision achieved with head-mounted eye trackers, there remain critical process-oriented questions that cannot be answered with this methodology. In particular,

this methodology sacrifices the spatial and temporal resolution achieved with remote eye trackers, because it is much more difficult to determine precisely where an infant looks and what constitutes a fixation. Although some of the previously reviewed studies imply that fixations are measured, the dependent measure is limited to measuring duration of looking based on consecutive gaze samples within a specific AOI. This measure is thus related to dwell time (total time looking at an AOI from entry to exit), but not the individual fixations that comprise our acquisition of visual information. Our eyes scan the visual world via saccadic movements and fixations on selected regions to enable foveation for high-resolution sampling of visual information (Guerrasio et al., 2010). The number and duration of fixations are determined by both bottom-up (e.g., image statistics, stimulus salience) and top-down (e.g., strategies, goals) processes (Tatler et al., 2017). We are unable to probe these processes directly in naturalistic (as opposed to experimental) situations, but measuring when fixations shift and how long they remain focused on the face or on hands and objects offers some important insight into when and how eye direction or manual actions are attracting infants' attention. In particular, the duration of a fixation reflects the encoding of the stimulus features as well as decisions regarding where and when to look next (Tatler et al., 2017).

Typically, infants are studied with remote eye trackers while they look at static visual stimuli or watch videos of people from a third-person perspective (e.g., Frank et al., 2012). One solution to studying social attention during social interaction with a remote eye tracker is to test infants' visual behavior to the video image of a social partner filmed from a first-person perspective. Boyer, Harding, and Bertenthal (2020) tested 8- and 12-month-old infants and adults with high-resolution eye tracking while they viewed videos of actors performing infant-directed actions on objects from a first-person perspective. For example, one video

demonstrated to infants how to attach a bow to the top of a wrapped gift box. From the participant's perspective, the actor appeared to be looking at the infant's or adult's face when her gaze direction was oriented toward the screen; alternatively, the actor's eyes were averted as she appeared to look at one of the objects on the table. As such, these videos simulated a social exchange while the face and actions of the actor were continuously changing (Figure 1). Although this experimental set-up is not fully interactive because the actor does not respond contingently to the infant's behavior, it may be less critical than assumed. In a very detailed observational study of infants and parents, Deák et al. (2018) report that infants between 3 and 11 months of age follow their mothers' visual attention a majority of the time.

The opportunity to measure visual attention in terms of the sequence and duration of fixations offered some important and novel insights into how infants interacted with a social partner. Fixation durations were tested in response to age, gaze direction (toward or away from the viewer), and action type (actions involved either manipulating an object – object-directed – or holding and waving an object – infant-directed). Although all three age groups fixated longer on hands-and-objects during the actor's averted as opposed to direct gaze, their fixation durations were shorter when looking at hands-and-objects than when looking at faces (Figure 2). This result may seem inconsistent with the head-mounted eye tracking results suggesting that infants look longer at hands-and-toys than at faces, but, in fact, it is consistent. In order to compare the two sets of findings, it is necessary to compute the number of consecutive fixations focused on the same AOI (i.e., dwell time), because the head-mounted eye tracking results are not based on fixations but rather cumulative looking times (Figure 3).

The reason that measuring individual fixations is noteworthy is that it reveals how infants processed actions on objects. Each video included two or more objects that underwent

continuous transformations in orientation and location as they were manipulated. As a consequence, it was necessary for observers to continue to look at the objects over time, but it was also necessary for them to frequently shift their overt attention (i.e., fixation) from one location to another as the objects were manipulated by the hands. By contrast, dwell times on the face involved only one or two fixations, because there was much less movement – associated primarily with head turns and facial expression. Thus, fewer fixations were necessary to encode the information communicated by the face while watching each video. In sum, these results suggest that looking at faces recruited significantly less visual attention presumably because the face changed very little over time with the exception of shifts in gaze cues which were processed with one or at most two fixations, whereas the processing of actions on objects required three to six fixations.

One especially important innovation associated with the Boyer et al. (2020) study is the development of a method for measuring gaze shift latencies based on fixations following the onset of social cues. As can be seen in Figure 4, both 8- and 12-month-old infants shifted their attention away from the face (and to the hands-and-objects) following a shift toward object-directed gaze, but only 12-month-old infants shifted their attention toward the faces in the same manner as adults following the onset of direct gaze by the social partner. Similarly, only 12-month-old infants and adults were more likely to shift their gaze toward the face following the onset of an infant-directed action. By contrast, the likelihood of shifting gaze from the face following the onset of an object-directed action increased for all three age groups. The primary conclusion is that 8-month-old infants are less responsive to direct gaze and infant-directed actions than are 12-month-old infants. This is predictable since both cues are associated with the intention by the social partner to communicate, and social communication involving ostensive

cues (e.g., pointing, direct gaze) becomes much more frequent between 8- and 12-months of age (Lock & Zukow-Goldring, 2010). By contrast, object-directed actions “in the wild” are beginning to capture attention by 3- to 4-months of age (Deák et al., 2018).

There were a number of other novel and informative findings that emerged from this study but the main point is that they were revealed only when the distribution of visual attention was analyzed in terms of the durations and locations of the participants’ fixations. These fixations specify greater spatial and temporal precision than available from observational measures or even head-mounted eye tracking measures. Our point is not that these measures are better or more informative than other measures calculated at slower time scales, but rather that our understanding of social attention and social interaction is improved when we consider the processes unfolding at each time scale in the context of the others.

IV.3. Neural oscillations and synchrony during social interaction. In addition to measures of infant gaze behavior, a small but growing number of research groups have started to assess infants’ brain activities during naturalistic social exchanges. This endeavor comes with particular challenges as neural measures, especially electroencephalogram (EEG), are prone to artifacts when movement is not constrained and participants cannot be instructed (Hoehl & Wahl, 2012). At the same time, the application of EEG or functional near-infrared spectroscopy (NIRS) is relatively inexpensive compared to MEG or MRI and mainly requires the attachment of a cap or headband containing the respective recording channels on the head, so both methods are feasible for working with infants. Most importantly, neural measures allow insights into dynamic processes of attention and perception in real time, in the case of EEG with a sampling rate of 500 or 1,000Hz. These methods can offer crucial information in addition to gaze because the duration of an infants’ look does not always tell us how much attention they really devote to the visual

stimulus and how efficiently it is encoded (Reynolds et al., 2010; Reynolds & Guy, 2012). Thus, we point to EEG and NIRS as useful methods helping us to uncover covert processes and fluctuations of social attention as they play out in real time during dynamic interactions. As outlined below, these methods have the potential to elucidate some of the very fundamental neural mechanisms through which infants align their attention and representations of the world with other people.

The first study measuring infant EEG during a live social interaction with an adult experimenter addressed the potentially arousing effects of eye contact during a triadic person-person-object interaction (Striano et al., 2006). Nine-month-old infants interacted with an experimenter while their brain activities were assessed through EEG. The experimenter was seated next to a computer monitor where an object would appear from time to time. Through headphones the experimenter was instructed to either establish eye contact with the infant or look toward the screen and not address the infant before the next object appeared. Infant and experimenter then watched the object on the screen. Although the same objects were presented in both the eye contact and the no-eye contact conditions in this within-subjects design, there were remarkable differences in infants' brain responses to the objects depending on the experimental manipulation. These differences were not apparent from infants' looking behavior alone, as infants looked at the objects presented on the screen similarly in both conditions.

Most importantly, event-related potentials revealed that infants responded with substantially higher amplitudes of the mid-latency Nc component over fronto-central channels to objects following a brief instance of eye contact. As the Nc was related to other measures of infants' attention and effective encoding in previous research (Reynolds & Richards, 2005), this new finding suggested that infants processed objects with increased attention following eye

contact with the experimenter. Subsequent re-analysis of the data with time-frequency analyses revealed further that infants showed suppression of 5-7 Hz alpha band activity, that is increased brain activity, over wide areas of the brain in the eye contact condition, which was not the case in the no-eye contact condition (Hoehl et al., 2014). This latter finding, corroborates the notion that prior eye contact leads to privileged processing of mutually attended information in 9-month-old infants. While previous behavioral research already showed that eye contact during familiarization facilitates 9-month-olds' later recognition of jointly attended objects (Cleveland & Striano, 2007), this EEG study offered first glimpses into infants' processing of jointly attended objects in real time, during the interaction. Yet, this research was still limited by focusing solely on the brain activities of the infant and not including the dyadic partner.

Leong and colleagues were also interested in the effects of eye contact during adult-infant interaction (Leong et al., 2017). In addition to measuring infants' EEG in 8-month-old infants, they also assessed adults' EEG during the exchange, thus implementing a so-called hyperscanning paradigm (Babiloni & Astolfi, 2014; Dumas, 2011; Hasson et al., 2012). Neural oscillations, measured on the scalp with EEG, reflect fluctuations in the excitability of underlying neuronal populations (Henry & Herrmann, 2014; Peelle & Davis, 2012; Schroeder et al., 2010). These band power oscillations, especially in the lower frequencies such as delta (0.1-3Hz) and theta (4-8Hz), are suggested to reflect waxing and waning levels of dynamic attention (Henry & Herrmann, 2014; Jones, 1976; Schirmer et al., 2016). If two individuals are aligned with regard to their dynamic attention and brain oscillations, mediated in part through mutual entrainment to communicative signals such as speech (Hasson et al., 2012; Zion Golumbic et al., 2013), then their interactions will result in more efficient communication and coordination (Novembre et al., 2017; Pan et al., 2020).

The main hypothesis in the study by Leong and colleagues was that mutual eye contact could induce a phase-reset of both the infant's and the adult's ongoing oscillatory brain activities resulting in increased mutual synchrony. To test this prediction, they had an adult experimenter sing nursery rhymes to the infant either while looking directly at the infant or with gaze averted to the side of the infant. Using partial directed coherence, a measure of mutual bidirectional influences of infant and adult time series of EEG data, the authors showed higher levels of mutual influence or connectivity between infants and adults during eye contact compared to the averted gaze condition. It remains to be tested in future research whether this increased interpersonal coupling of brain activities can indeed be attributed to a simultaneous phase-reset in both infants' and mothers' time series which is a plausible mechanism, but will require further analysis of phase-locked activity around the onsets of instances of mutual gaze.

In contrast to the studies reviewed in the previous section on eye tracking, Striano and colleagues (2006) and Leong and colleagues (2017) tested infants with rigidly structured interactions, and they focused exclusively on the effects of eye contact, which though striking and important, are by no means the whole story of how infants direct their attention during live social exchanges. In order to improve upon the ecological validity of the testing, Wass and colleagues conducted a study allowing for more natural social interactions between mothers and their 12-month-old infants playing with toys while measuring dual-EEG (Wass et al., 2018). During a joint play condition, mothers were asked to silently play with a toy and to engage their infant in the play. During a solo play condition, mothers and infants played independently with the toys while separated by a screen. During the session, EEG was acquired from infants and mothers and their looking behavior was coded manually frame-by-frame from video recordings at a sampling rate of 30 Hz.

The results revealed that during solo play, infants' theta power statistically predicted their looking behavior toward the toys. As infants' 4-6 Hz theta band activity has been implicated in attention and memory encoding processes (Begus & Bonawitz, 2020), this likely reflects infants' endogenous attention control when engaging with toys on their own. Interestingly, this forward-prediction of theta activity was substantially lower during the joint play condition, suggesting less endogenous control in joint vs. solo play, which is presumably due to maternal guidance of infants' attention during joint play. Furthermore, infants attended to the objects more during joint play than solo play. This sustained attention continued for longer in dyads where infants' changes in looking behavior (a proxy for attention) were followed by increases in theta power in the mother. It thus seems that dyads in which mothers closely track their infants' attention during joint play are able to maintain high levels of infants' object-directed attention for longer.

This study illustrates nicely the benefits of combining micro-analyses of behavior (in this case gaze) and brain activities (in this case theta oscillations) during an interaction. The behavioral analysis by itself informed us only that infants showed longer sustained object-directed looking during joint play than during solo play, which leaves room for multiple interpretations of how and why infants directed their attention. Only by adding analyses of brain activities was it possible to reveal that infants' endogenous attention control was actually higher during solo play relative to joint play and that mother's sensitive tracking of their infants' attention predicted gains in infants' sustained attention during joint play.

Despite these interesting and promising first results, we have to point out that there are challenges associated with assessing infants' EEG during a live interaction. In particular, data quality is an issue as all kinds of (eye) movements and vocalizations inevitably result in artifacts and data loss. Indeed, most EEG studies retain only 50% of the infants in the final sample (Stets,

Stahl, & Reid, 2012). Another neuroimaging method that is less artifact-prone is functional NIRS which can be used to assess hemodynamic responses, that is changes in the oxygenation of blood in cortical areas associated with brain activation (Lloyd-Fox et al., 2010).

Piazza and colleagues simultaneously measured brain activities from 9- to 15-month-old infants and an adult experimenter (Piazza et al., 2020). In two within-subject conditions, infants and adults either played together, engaging with books, toys and nursery rhymes, or infants and adults interacted with another person, whose brain activity was not assessed. As predicted, higher correlations between infants' and adults' NIRS data were found when both were engaged in an interaction with each other as opposed to another person. Additionally, the authors report links between interpersonal neural synchrony and dyadic behaviors, such as mutual gaze, joint attention (operationalized as looking simultaneously at the same object) and infants' smiling. Specifically, the correlation between infants' and adults' brain activities was significantly decreased after regressing out effects of mutual gaze and infants' smiling.

As nicely illustrated in the studies by Wass et al. and Piazza et al., hyperscanning of brain activities combined with detailed behavioral coding and analyses is a promising approach to better understand the dynamic processes involved in infants' real-time interactions with adults (Hoehl & Markova, 2018; Markova et al., 2019; Nguyen, Bánki, et al., 2020). This approach is particularly useful when trying to determine which behaviors of the dyad mediate synchronized or mutually predictive patterns of neural activity (Hamilton, 2020). While the preceding two studies focused mostly on gaze, Nguyen and colleagues were particularly interested in the role of touch in establishing mother-infant synchrony (Nguyen et al., in preparation). They combined dual-fNIRS with dual-electrocardiogram (ECG) of mothers and their 4- to 6-month-old infants in three conditions: joint watching of a video without mutual touch, joint watching of a video with

touch (infant seated on the mother's lap) and a dyadic free play interaction without toys. Both mother-infant brain activities as well as respiratory sinus arrhythmia (RSA)¹ were more synchronized during free play as compared to the two joint watching conditions, suggesting that mother-infant synchrony depends on mutual adaptation and engagement more than on shared perceptual input. Interestingly, neural synchronization, in particular, was also enhanced when mother and infant were able to touch each other relative to the joint watching condition without touch (see Figure 5). Likewise, higher durations of affective touch, such as soft stroking, during the free play interaction were also related to higher neural synchrony (see Figure 6), but not RSA synchrony. These results point toward an interesting functional dissociation between physiological and neural synchrony. Whereas physiological synchrony seems to play a role in co-regulation of infants' arousal, especially during peak levels of arousal (Wass et al., 2019), neural synchrony reflects the mutual engagement and reciprocity of the dyad and relates to successful coordination and communication between caregiver and child (see also Nguyen, Schleihau, et al., 2020a, 2020b). Further research on this tentative conclusion is clearly necessary, though, as a direct comparison of measures of neural and physiological synchrony is methodologically challenging and the relations of physiological and neural rhythms are not yet fully understood even within the individual organism (Klimesch, 2013).

Together, the studies summarized in this section offer a preview of the research questions that are possible to address when combining multiple measures at varying time scales of interest during naturalistic live social exchanges. We can now track fluctuations of (joint) attention over the course of a dynamic interaction (Hoehl et al., 2014) and assess mutual influences of infants

¹ RSA is a measure of cardiac vagal tone which is derived from heart rate variability at the frequency of breathing and serves as an indicator of the parasympathetic influence on heart rate (Porges, 1991).

and adults that are not apparent from behavioral coding alone (Wass et al., 2018). At the same time, detailed behavioral analyses offer invaluable information on the dyadic behaviors associated with high levels of neural synchronization, in particular mutual gaze (Leong et al., 2017; Piazza et al., 2020), infant positive affect (Piazza et al., 2020) and maternal affective touch (Nguyen et al., in preparation). In the final section of this chapter we synthesize some of the major conclusions and point out several important future directions for the field.

V. Summary and Conclusions

The goal of this chapter was to explore the development of social attention through the lens of social interaction and a second-person perspective. This perspective obviates the need for social cognition as a prerequisite for social attention, because our understanding of others is constituted within real-time perception-action loops between infants and their social partners. Social attention and understanding is specified directly by these interactions in context, and does not necessitate any inferences based on the mental states of others (e.g., beliefs, desires) (Gallagher, 2008). Through familiar and repeated interactions with caregivers, infants' social attention skills and understanding continue to improve. The engine for these developmental changes is that the brain functions like a 'prediction machine' (Clark, 2013). Social exchanges occur on a time scale that requires individuals to act prospectively, not retrospectively, because there is insufficient time for social interactions to proceed smoothly and continuously if inferences about each others' mental states (e.g., intentions, desires) are necessary (Yu & Smith, 2016). As such, social interactions involve predictive processing by both infants and caregivers, and these social interactions will become better coordinated as both participants learn to reduce their prediction errors and thereby improve their understanding of each other (E. Z. Tronick, 1989).

As we discussed, much of the previous social attention research has focused on paradigms designed to test how infants' attention is influenced by social cues when the visual environment is highly controlled and often impoverished in order to avoid distraction from the task. These studies, however, tell us little about the dynamic processes of social attention in the real world. Infants' everyday social experiences are much more complex than implied by these studies and require that infants choose among different social cues available at the same time, for example gaze, mouth movements and manual actions or gestures. Furthermore, sustaining attention to a jointly attended object, especially in the presence of multiple distractors in a complex environment is likely a critical feature of how infants coordinate attention with other people in the real world (Yu & Smith, 2016). While our intent is not to dismiss the usefulness of simplified and controlled experiments for answering specific research questions, we do wish to sound a *call to action* for the wider application of more ecologically valid paradigms for studying social attention. Given recent technical advancements, such as head-mounted eye tracking and mobile EEG/ NIRS, it is now possible to perform more and more detailed analyses of infant behaviors and brain activities in real time during naturalistic social exchanges.

These new technically-sophisticated studies offer unprecedented insights into the dynamic processes of infant-caregiver social attention. We can now track in much greater detail fluctuations over time with regard to object-directed attention as well as social attention and how these processes relate to one another. The study of such fluctuations demands a dynamical systems approach that conceptualizes attention as a dynamic process rather than a static construct or outcome of development and that focuses on the dyad as the unit of analysis, rather than the infant.

Combining measures of behavior and brain activity of the dyad turns out to be a promising approach for assessments at multiple time scales simultaneously. This is particularly relevant when trying to better understand how people align with one another over time (Hamilton, 2020). Delineating the hierarchical structure of rhythms at different frequencies embedded in verbal conversation, for instance, has promoted insights into how people tune in to relevant information and tune out irrelevant signals (Zion Golumbic et al., 2013). We have yet to develop a comparably deep understanding of the different time scales at which social attention is manifested, but recent studies reviewed in this chapter offer some promising directions.

This review suggests that the unfolding of these dynamic patterns and regularities will be informative to our understanding of real-life coordination in infant-caregiver interaction, especially because these interactional patterns allow for mutual predictability which is highly conducive for communication and information transfer (Hoehl et al., 2020; Koban et al., 2019). As we have highlighted in this chapter, increasingly effective mutual prediction within the caregiver-infant dyad is one of the main factors underlying the continuous development of social attention over the first year, resulting in increasingly smooth and mutually adaptive caregiver-infant interaction. Delineating these processes in healthy development promises to further our understanding of at-risk caregiver-infant interactions. For instance, mothers with postpartum depression and/or anxiety may find it challenging to sensitively attune to their infants and *vice versa*, resulting in difficulties in mutual prediction and interactional coordination (Beebe et al., 2008; Granat et al., 2017; Tronick & Reck, 2009). A consideration of how predictive processing plays a formative role in early development may offer new insights into impaired interaction patterns and also further our understanding of classic paradigms for studying caregiver-infant interactions, such as the still-face paradigm (Adamson & Frick, 2003; Tronick et al., 1978). The

challenge for the future is to continue to refine current methods as well as develop new methods for studying mutual prediction and reciprocal interactions within caregiver-infant dyads.

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Table 1.1: Time scale of human action (as defined by Newell, 1990) and associated research methods

Scale (sec)	Time units	System	World	Method
10^7	months		Social Band	Longitudinal studies
10^6	weeks			
10^5	days			
10^4	hours	Task	Rational Band	Behavioral & verbal responses
10^3	10 minutes	Task		
10^2	minutes	Task		
10^1	10 sec	Unit task	Cognitive Band	Eye tracking, fNIRS, fMRI, Behav. coding
10^0	1 sec	Operations		
10^{-1}	100 ms	Deliberate act		
10^{-2}	10 ms	Neural circuit	Biological Band	ECG, EEG, MEG, RT
10^{-3}	1 ms	Neuron		
10^{-4}	100 μ s	Organelle		

fNIRS = functional Near Infrared Spectroscopy; fMRI = functional Magnetic Resonance Imaging; RT = response time; ECG = electrocardiography; EEG = electroencephalography; MEG = magnetoencephalography

Figure 1

Figure 1. Screen shot from one of the stimulus videos with an overlay of the AOIs. The numerical dimensions of each AOI correspond to their mean size based on all frames of the video. Reprinted with permission from Boyer et al. (2020).

Figure 2

Figure 2. Mean fixation durations as a function of age, gaze direction, and action type. Top panel displays fixations directed to the face, and bottom panel displays fixations directed to hands-and-objects. (Error bars represent ± 1 standard error of the mean.) Reprinted with permission from Boyer et al. (2020).

Figure 3

Figure 3. Mean dwell times as a function of age and gaze location. (Error bars represent ± 1 standard error of the mean.) Reprinted with permission from Boyer et al. (2020).

Figure 4

Figure 6. Mean changes in proportions of fixations to the face following changes in gaze direction or action type as a function of age. Baseline was determined by calculating the mean proportion of looking at the face during each of the four social cues (direct, averted, gesture, object-directed) for each age separately. It is represented as the shaded horizontal region corresponding to confidence intervals of the means: 8-month-old infants = red; 12-month-old infants = blue; adults = yellow. (Error bars represent ± 1 standard error of the mean.) Reprinted with permission from Boyer et al. (2020).

Figure 5

Figure 5. Wavelet transform coherence (WTC) values between the NIRS signals of 4- to 6-month-old infants and their mothers during three within-subject conditions. Interpersonal coherence was the highest during free play (FP), followed by joint watching of a video while the infant was seated on the mother's lap (proximal watching, PW). Lowest coherence was observed during distal watching (DW) without physical proximity and touch.

Figure 6.

Figure 6. During free play a significant positive correlation was found between mother-infant neural synchrony (WTC) and the duration of spontaneous affectionate touch, that is soft stroking.