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Contingency and Synchrony: Interactional Pathways Toward Attentional Control and Intentional Communication

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Abstract

In this article we examine how contingency and synchrony during infant–caregiver interactions help children learn to pay attention to objects and how this, in turn, affects their ability to direct caregivers' attention and to track communicative intentions in others. First, we present evidence that, early in life, child–caregiver interactions are asymmetric. Caregivers dynamically and contingently adapt to their child more than the other way around, providing higher-order semantic and contextual cues during attention episodes, which facilitate the development of specialized and integrated attentional brain networks in the infant brain. Then, we describe how social contingency also facilitates the child's development of predictive models and, through that, goal-directed behavior. Finally, we discuss how contingency and synchrony of brain and behavior can drive children's ability to direct their caregivers' attention voluntarily and how this, in turn, paves the way for intentional communication.

Contents

1. INTRODUCTION

> We must perceive in order to move, but we must also move in order to perceive.
>
> —James Gibson (1979, p. 223)

We spend the majority of our early-life waking hours in the presence of an adult caregiver (Trevarthen 2001). Consequently, most of our early cognitive processes take place and are constructed in social contexts. Yet, much of our current understanding about how infants learn to pay attention to things and events around them, and the neural processes that support this, comes from research that examines children in isolation.

Research examining how we develop the capacity to pay attention has traditionally focused on controlled, researcher-driven paradigms examining how infants respond to stimuli that appear and disappear on-screen or to an experimenter performing a specific activity (e.g., Orekhova et al. 2006, Richards & Turner 2001, Throm et al. 2023). This has allowed researchers to consider the properties both of the individual who is paying attention (e.g., their age) and of the stimulus or events that they are paying attention to (e.g., their salience or complexity). By manipulating the familiarity, complexity, comprehensibility, and salience of the stimuli presented (e.g., Cohen 1972, de Urabain et al. 2017, Oakes et al. 2002, Richards 2010, Stallworthy et al. 2020), researchers have been able to understand how the neural substrates of different facets of attention, measured in terms of behaviors such as look duration, number of fixations, resistance to the distractor, and so on change not only over developmental time but also between different situations and across neurodevelopmental disorders (Cohen 1972, Colombo & Cheatham 2006, Forest & Amso 2023, Hendry et al. 2019, Johnson et al. 1991, Oakes 2023b).

Over the past decade, increasing efforts have been made to take a different approach by instead researching how children spontaneously deploy and structure their attention in real-world settings during unconstrained free behavior with their caregiver (e.g., Abney et al. 2020; Franchak et al. 2018; Le et al. 2021; Wass et al. 2023; Yu & Smith 2013, 2016). This approach allows for the study of a variety of important features of attention that lab-based experimental studies are unable to capture. For example, during free behavior, infants' attention durations are longer toward objects that they attend to jointly with other people than those they attend to on their own (Yu & Smith 2016). Caregiver behaviors influence the durations of individual attention episodes moment by moment (Bakeman & Adamson 1984; McQuillan et al. 2020; Phillips et al. 2023a; Schroer & Yu 2021; Yu & Smith 2016, 2017), and they also influence the long-term development of the child's capacity to sustain and control their own attention patterns during later life (Feldman et al. 1999, Mason 2018, Mason et al. 2019, Miller & Gros-Louis 2013).

These two ways to study infants' attentional development—in isolation or within social interactions—map onto an epistemological divide between two theoretical traditions in developmental science. On the one hand are theories that mainly construe attentional development as the product of maturation that depends on the growth and reorganization of specific brain structures (Colombo & Cheatham 2006). On the other hand are theories that consider attention as being constructed through experiences, in particular social experiences accrued during interactions with other agents (Fogel & Garvey 2007). Here, we attempt to bridge these two traditions by showing how social interactions can shape development of an infant's capacity to pay attention to objects and things around them in solo settings during later life and, in turn, how social interactions can influence a child's developing capacity to (*a*) direct their caregiver's attention voluntarily, (*b*) communicate their interest to others, (*c*) proactively engage others in attention sharing, and (*d*) understand the principles that govern conventional communication, including the referential nature of words. In doing this, our aim is to illustrate the mechanisms through which our moment-by-moment real-world interactions can drive the emergence of key cognitive faculties that are more traditionally accounted for in terms of maturation, growth, and reorganization in the brain (cf. Oakes 2023a,b). We discuss how, by impacting infants' attention, social interactions bootstrap the emergence of intentional and conventional communication.

In the sections that follow, we first discuss how children learn to pay attention to objects during social interactions (Sections 2 and 3), before we go on to consider children's ability to direct their caregivers' attention and their communicative development (Sections 4–6). First, in Section 2, we characterize early child–caregiver interactions as primarily asymmetric, driven by caregivers dynamically and adaptively changing their own behaviors contingently on their child. During early childhood, infants' attention is allocated largely stochastically and is mainly salience-driven. Caregivers dynamically alter the salience of their own face and voice to engage their child's attention via low-level attention capture. In Section 3 we describe how, once a child's attention is engaged, caregivers further modify their own behavior, providing additional semantic and contextual information about whatever the child is engaged with. We discuss the neural mechanisms through which, by providing semantic and contextual information during an attention episode, caregivers both amplify the child's attention during that episode and also promote the long-term development of the child's capacity to pay attention to things on their own during later development.

In Section 4, we describe how contingency can contribute to the development of volitional control via predictive coding. In Section 5, we discuss how contingency can cause temporal coordination of behavior across modalities and how this can lead to brain synchrony independent of behavioral synchrony, with possible impacts on attention. In Section 6 we discuss how these two interactional parameters—contingency and synchrony—also support infants' discovery of intentional communication by fostering their attentional development. Finally, in Section 7, we discuss potential applications of these ideas for understanding atypical development and directions for future work.

2. "CATCH ME IF YOU CAN": ASYMMETRY, CAREGIVER SALIENCE, AND LOW-LEVEL ATTENTION CAPTURE

Early experimental research emphasized that infants are inherently sensitive to ostensive signals, such as whether or not an adult partner is looking directly at them (Farroni et al. 2004, 2007) and an adult partner's direction of gaze (Senju & Csibra 2008). This research has been primarily used as the basis for theoretical arguments that, from early development, adults use ostensive signaling to directly and didactically scaffold their child's attention, for example, by building a structure of how and when they pay attention and encouraging the child to follow their attentional focus (Bánki et al. 2024, Okumura et al. 2020). This approach is consistent with pedagogical approaches that primarily emphasize a one-way flow of information from an adult sender to a child receiver (Csibra & Gergely 2009).

However, more recent research that examined infant attention in real-world settings during free-flowing infant–caregiver interactions has reported a picture that seems remarkably at odds with the findings of these studies. This research suggests that during shared toy play, for example, infants in fact seem to be frequently unresponsive to caregiver signals. For example, 5-, 11-, 12-, and 14-month-old infants rarely follow the eye gaze of their social partners during toy play (Perapoch Amadó et al. 2023a, Goupil et al. 2024, Phillips et al. 2023b, Yu & Smith 2013), relying instead on their caregiver's hand actions and the physical positioning of the objects to join shared attention episodes (McQuillan et al. 2020). Recording infant brain activity during free-flowing interactions, Marriott Haresign and colleagues (2023) also found no evidence that 11-month-old infants' brain activity is sensitive to a caregiver's initiation of mutual gaze during play. In comparison with the clear and repetitive stimuli presented in experimental paradigms during free-flowing interactions, ostensive signals are generally rapid, unpredictable, and noncontiguous (Fogel & Garvey 2007) and potentially, therefore, difficult to track during real-world interactions (Yu & Smith 2017). These and other recent findings (Çetinçelik et al. 2022, Menn et al. 2022, Tan et al. 2022) are giving rise to a theoretical shift away from approaches that emphasize infants' inbuilt sensitivity to social signals, in particular eye gaze signals, during early attentional development and toward an approach that emphasizes the role of culturally situated social interactions and embodied explorations in driving the development of attention (Schroer & Yu 2022, Suarez-Rivera et al. 2019, Yu & Smith 2013).

It is believed that, at birth, attention is largely involuntary, exogenously driven, and primarily under the control of subcortical structures (Colombo 2001, Gardner & Karmel 1995, Reynolds & Romano 2016, Richards 1997). Attention shifts happen periodically, two-to-three times per second (Wass 2022). When 2-to-14-week-olds view a static image with sharp (highly salient) contours, 14-week-olds consistently direct their saccades toward salient contours, but 2-week-olds do not (Bronson 1990, 1994). Other research has looked at how easy it is to recreate infants' spontaneous attention behaviors using a stochastic generative model in which the timing of gaze shifts is random and unaffected by what is present at the point fixated. The model produced a good match for gaze behavior in 1-month-olds but was less accurate at reproducing behavior in 3-month-olds (Robertson 2014). These findings suggest that, over time, infant attention becomes gradually more modulated both by information present at the point being fixated and, eventually, by the viewer's own goals (Colombo & Cheatham 2006, Oakes 2023b, Oakes et al. 2002, Wass et al. 2023). Up until that point, though, how do infants manage to successfully coordinate their attention with others?

During an interaction, even from early development, influences across an interacting dyad are bidirectional. Studies that examined modalities including visual attention, facial and vocal affect, orientation, and touch have all shown both that caregivers adapt their behaviors contingently on the child and that children adapt their behaviors contingently on the caregiver (Beebe et al. 2016, Cohn & Tronick 1988, Feldman et al. 1999, Murray et al. 2016, Yu & Smith 2016). However, particularly during early infancy (Beebe et al. 2016, Perapoch Amadó et al. 2023b), the interdependencies between infants and caregivers are relatively more asymmetric: Caregivers adapt their behaviors contingently on the child more than vice versa (Beebe et al. 2016, Phillips et al. 2023b).

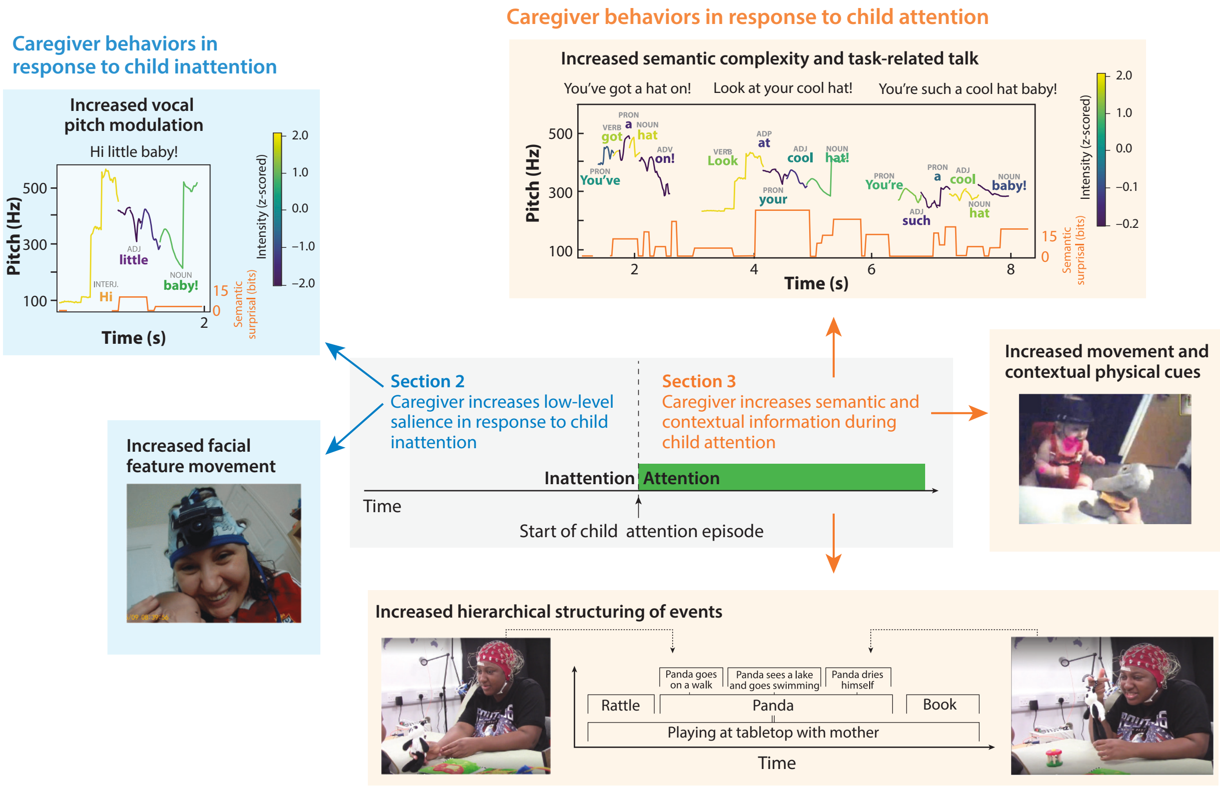

Figure 1

Schematic illustrating caregiver behaviors in response to child inattention (Section 2) and caregiver behaviors in response to child attention (Section 3).

The same finding has also been shown in studies that measure physiology and neural activity. For example, caregivers' neural activity during free-flowing interaction tracks infant attention, but infants' brain activity does not track their caregivers' (although it does show sensitivity to certain caregiver behaviors, as discussed in Section 4) (Wass et al. 2019; see also Phillips et al. 2023b). And, whereas vocal behavior in 12-month-olds is heavily contingent on their own autonomic arousal state, caregivers' vocal behavior toward infants is more contingent on the infant's autonomic state than on their own (Perapoch Amadó et al. 2023a).

When young children lose attention during a joint interaction, caregivers typically seek to re-engage them via low-level attention capture (Yu & Smith 2012), targeting early developing mechanisms (Colombo 2001, Johnson 1990) that preferentially orient attention to visual (Itti & Baldi 2009, Mital et al. 2010) and auditory (Huang & Elhilali 2017) salience (see **Figure 1**). For example, caregivers may respond to decreases in child attention by increasing their own auditory salience (e.g., by increasing the rate of modulation of the voice), but then, when the children's attention is re-engaged, may downregulate their salience (Phillips et al. 2023a). Together, these findings suggest that, early in development, caregivers dynamically change their own behaviors moment by moment contingently on the attentional state of their child, targeting low-level attention capture to engage their attention. Infants, in contrast, rarely modulate their own behaviors contingently on the attention state of the caregiver.

3. "YOU'VE CAUGHT ME, NOW TRY TO KEEP ME": SEMANTIC AND CONTEXTUAL CUES, COMPREHENSION, AND SUSTAINED ATTENTION

Above, we consider how caregivers respond to child inattention by increasing the salience of their voice and face to attract a child's attention. But what happens when they succeed, and a child starts to pay attention? The behaviors of a caregiver during a child's attention episode remain influential in determining how long that attention episode lasts, but the tactics they use change.

In this section we discuss how caregivers use higher-order features of the interaction, such as semantic and contextual cues, to sustain a child's attention after it is engaged. We also discuss the possible neural mechanisms through which, by providing additional semantic and contextual information during an attention episode, caregivers both amplify the child's attention in the moment and promote the long-term development of the child's capacity to sustain attention on their own during later development.

Attention episodes where both child and caregiver look to the same object at the same time are more long-lasting than episodes where a child is paying attention to the same object on their own (Suarez-Rivera et al. 2019, Wass et al. 2018, Yu & Smith 2016). Episodes of concurrent infant and caregiver attention take on a self-sustaining character, known as attention inertia: The longer an attention episode lasts, the more its likelihood of ending during the next successive time interval diminishes (Wass et al. 2018, 2023; Yu & Smith 2016). By following infants' attention patterns and selectively responding to their cues, caregivers amplify infants' attention states (see **Figure 1**). To use language from dynamic systems theory, caregivers help contribute toward establishing and maintaining short-term attention states as attractors (see **Figure 2**).

But how do they do this? Several complementary strategies have been documented. First, caregivers can provide a verbal commentary. For example, one study found that, when caregivers talk about the object that the child is currently playing with, this prolongs child attention durations more than other features such as touch (Schroer et al. 2019, Schroer & Yu 2021, Slone et al. 2023, Suarez-Rivera et al. 2019, Tamis-LeMonda et al. 2014). This is consistent with other findings that caregiver talk amplifies child attention durations toward objects in the short term (Baldwin & Markman 1989, Belsky 1980, Carvalho et al. 2019, Vales & Smith 2015) and that how caregivers

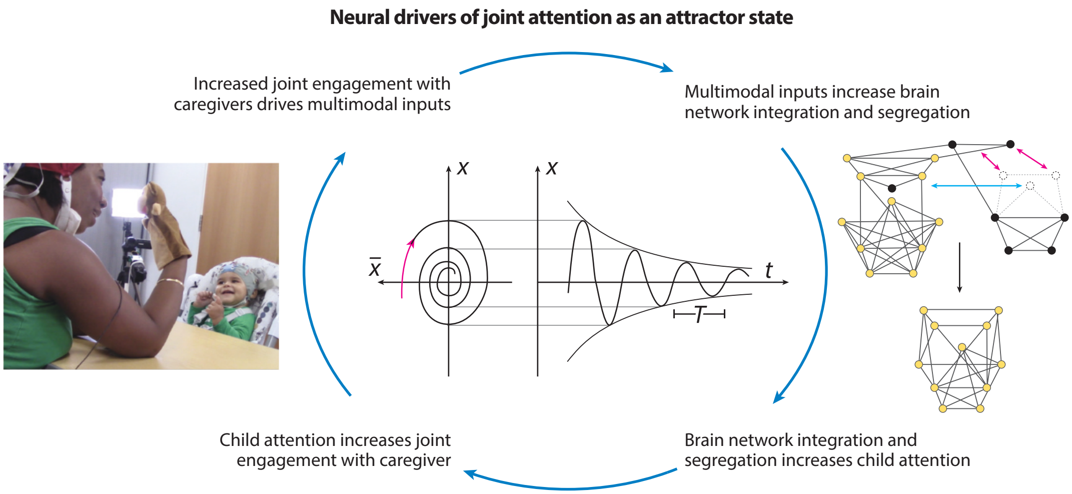

Figure 2

Schematic illustrating neural drivers of joint attention as an attractor state, as discussed in Section 3.

support and scaffold child attention predicts the child's capacity to pay attention on their own in solo settings during later development (Feldman et al. 1999, Geeraerts et al. 2019, Gueron-Sela et al. 2017).

Recent research is also starting to understand the neural mechanisms through which visual attention and object-related talk mutually amplify one another (Wass et al. 2023). These approaches view attention as a product of local cortical interactions that mutually reinforce one another through interareal connectivity (Buschman & Kastner 2015). Recent functional magnetic resonance imaging research with children and adolescents has, for example, described how endogenous attention control associates with increased functional system segregation at lower levels of the sensorimotor association axis, as well as with increased integration between hierarchically distinct levels within the axis (Keller et al. 2022). When hierarchically linked areas are active at the same time, the global representation of information through recurrent processing could be facilitated, supporting behavioral performance (van Kempen et al. 2021). Multimodal cues (such as accompanying a child's gaze toward an object with caregiver talk about that object) associate with more stable and better segregated coordination between spatially distributed regions of the brain (Just & Varma 2007), as well as with longer child attention durations (Burris & Brown 2014, Pempek et al. 2010). One possibility is that task-related caregiver talk may increase brain network integration and segregation. This, in turn, might increase selective attention, creating a self-sustaining cycle (see **Figure 2**).

A second strategy consists of acting on the object that is currently attended to by the child. For example, if a child pays attention to an object, caregivers often respond by picking up that object and bringing it closer to them or moving it around while they are talking (Anderson et al. 2022, Yu & Smith 2012). These actions have the effect of making the object more salient from the child's perspective, which further amplifies infants' initial attentional engagement (McQuillan et al. 2020, Sun et al. 2024, Yu & Smith 2016). Just as caregiver speech increases around object attention, adults' hand actions also markedly increased when infants followed their partner's attention toward an object (Custode & Tamis-LeMonda 2020, Franchak et al. 2018, Yu & Smith 2017). In both cases, a child paying attention to an object triggered caregiver behaviors that further amplified the child's attention.

A third, potentially important but underexplored, area that potentially includes both physical and semantic information is how caregivers and children act jointly to create events and sequences of events. When adults perform everyday actions, these naturally fall into event structures with hierarchically nested events (e.g., if my higher-order goal is to cook spaghetti, then my lower-order goals are to get out the pan, boil the water, put the spaghetti in the pan, etc.) (Zacks 2020). These events correspond to how information is encoded and retrieved from storage in the brain at specific moments (Hasson et al. 2008, 2015). When children play with caregivers, it is likely that, over development, they increasingly build hierarchically nested goals into their play. This is true whether the task involves building structures out of Duplo bricks (Schroer & Yu 2021) (where the higher-order goal is to build a tower and the nested subgoal is to find the correctly shaped bricks) or acting out scenes with dolls (where the higher-order goal is to tell a story of a doll visiting a castle and the nested subgoals are to go on a journey, reach the castle, open the door, etc.) (see **Figure 1**). It is possible that these event structures might be more hierarchical during caregiver play compared with solo play (Duncan et al. 2023) and that, once initiated, these higher-order goals may serve to prolong a play episode longer than it would have lasted in the absence of a goal. If so, this would offer a third pathway through which caregiver behaviors during an attention episode serve to prolong the length of that attention episode.

In summary, caregivers can use a variety of higher-order semantic and contextual actions to sustain a child's attention after it is engaged. These behaviors amplify and extend child attention over both short and long time frames by facilitating stability and segregated coordination between spatially distributed regions of the brain. Whether caregivers use a specific strategy or not likely differs as a function of a variety of factors, including their expectations regarding child development, caregiving styles, and so on. This remains understudied, however, due in part to the relative homogeneity of the populations typically involved in these studies and is, therefore, an important venue for future research.

4. "AHA, THAT GOT A RESPONSE": CONTINGENCY, PREDICTIVE PROCESSING, AND VOLITIONAL CONTROL

During early development, as we describe in Section 2, infants' behaviors are largely unpredictable and unconnected to the behaviors of their social partners, whereas adults are more likely to change their own behaviors contingently on the child. Some child behaviors typically induce a contingent response from their caregiver and others do not (Watson 1967). Some caregivers are also more likely to respond contingently to their child than others (Bornstein 2013, Tamis-LeMonda et al. 2013). In this section, we consider how consistent and contingent caregiver responses influence the development of predictive neural processing and, through that, support the development of goal-directed behavior.

We know, first of all, that infants are behaviorally and neurally sensitive to when an adult responds contingently to their behaviors (Phillips et al. 2023b, Rayson et al. 2019). In free-flowing tabletop play, 12-month-old infants do not consistently use their gaze or vocalize before an infant-initiated mutual attention episode, but they do show differential neural responses when a caregiver responds contingently to their initiations by following the child's attentional focus (Goupil et al. 2024, Phillips et al. 2023b). By following a child's initiation, caregivers also prolong the child's attention (Phillips et al. 2023a,b). Other research has also shown that responding contingently to an infant's gestures immediately improves the quality and quantity of the attention that they pay to objects (Mason 2018, Mason et al. 2019) and that when caregivers behave redirectively (i.e., noncontingently), infants' visual attention durations immediately decrease (Mason 2018, Miller & Gros-Louis 2013).

Importantly, though, adults are selective with respect to which behaviors they respond contingently to and which they do not. For example, in joint object play with 9-to-12-month-olds, caregivers respond more often to mature speech-like vocalizations and vocalizations that are accompanied by pointing and reaching gestures (Goldstein et al. 2010, Gros-Louis et al. 2006, Miller & Gros-Louis 2013, Murray et al. 2016, Warlaumont et al. 2014, Wu & Gros-Louis 2014). Over time, these statistical regularities build up, which is thought to allow a child to predict which of their behaviors will or will not elicit a caregiver response (Smith & Breazeal 2007). Indeed, neurocomputational associative learning accounts postulate that infants learn about their environment and how to act on it through repeated reinforcement, where the value given to an action is based on previous experience of how that action affected the environment. These accounts are derived from predictive processing models of brain functioning that suggest the brain is constantly updating probabilistic models of the environment on the basis of the associations between active motor behaviors and incoming sensory information (Clark 2013, Friston 2019, Köster et al. 2019).

Supporting this perspective are studies that examined change in volitional infant behaviors during free-flowing infant–caregiver interactions as a function of the frequency and the form of contingent maternal responses. For example, Bigelow & Power (2016) have shown that, at 5 months, caregivers' mirroring of their infants' facial affect during face-to-face interactions was most predictive of directive bids by the infant to re-engage the adult once the adult stopped interacting with them. In joint play interactions, the degree to which a caregiver responds contingently to infant vocalizations at 8 months predicts the number of directed vocalizations made by infants toward objects at 14 months (Wu & Gros-Louis 2014). Experimental paradigms have also shown that infants increase behaviors such as the rate of their pointing when an adult consistently provides information contingently on the focus of the infants' gesture (Begus & Southgate 2012, Kovács et al. 2014).

As well as reinforcing specific infant behaviors, contingent semantic responses by caregivers to reorientations in infant attention during joint play have also been shown to support infant word learning. Recording adult and infant gaze patterns with head-mounted eye trackers, Yu & Smith (2012) showed that 18-month-old infants learned object labels better during moments when the adult labeled an object at the same time the infants were looking toward that object. Goupil and colleagues (2024) have since replicated this finding in a tabletop play setting with 14-month-old infants.

What neural mechanisms might underpin these findings? First, there is some evidence to suggest that children's neural sensitivity to new information fluctuates dynamically and that there are times when the child is attentive and receptive to new information and times when they are not (Choisdealbha et al. 2023, Keshavarzi et al. 2022). Supporting this perspective, one study found that theta activity, considered a neural marker of endogenously driven attention (Orekhova et al. 2006), was significantly higher in the 1–2 s before infants led a shared attention episode toward an object compared with when they followed their caregiver's look (Goupil et al. 2024). Behavioral signals, such as a child initiating an attention shift toward an object, making an interrogative gesture such as pointing, or asking a question, signal to a caregiver that the child is in an attentive and receptive state (Begus & Southgate 2018, Begus et al. 2015, Goupil et al. 2024). This signaling allows caregivers to present new information at a time when an infant is optimally sensitive to receive it, thus maximizing the effectiveness of learning exchanges. Over time, infants come to expect to receive information in the time after they reorient their behavior during shared interactions on the basis of past experiences of information being provided contingently on their focus of attention.

Together, then, these findings suggest that contingent—and therefore predictable—caregiver responses allow children to generate probabilistic models of the environment, on which basis they can develop goal-directed behavior that involves redirecting their partner contingently on their own attention.

5. "IN THE SAME PLACE AT THE SAME TIME": CONTINGENCY, SYNCHRONY, AND STATE MATCHING

The distinction between contingency and synchrony is quite clear. Contingency is a lagged relationship in which changes in partner A forward-predict changes in partner B. Contingency is directed (A→B is not the same as B→A). Synchrony, in contrast, is a concurrent relationship: When partner A is high (or low), partner B is low (or high). Synchrony is, therefore, undirected (A→B is the same as B→A) (see **Figure 3**).

In effect, however, contingency and synchrony tend to co-occur. In this section, we discuss two types of concurrent temporal coordination that arise from contingency. The first is where contingency causes temporal coordination of behavior across modalities (e.g., I look at an object and in response you provide the verbal label for what I am looking at). This leads to processes that co-occur in time across a dyad (e.g., object labels being presented at times of peak attentional engagement from the child), but it does not lead to partners being in the same behavioral state at the same time. The second is where contingency causes actors to be in the same behavioral state at the same time (e.g., I smile at you and you smile back).

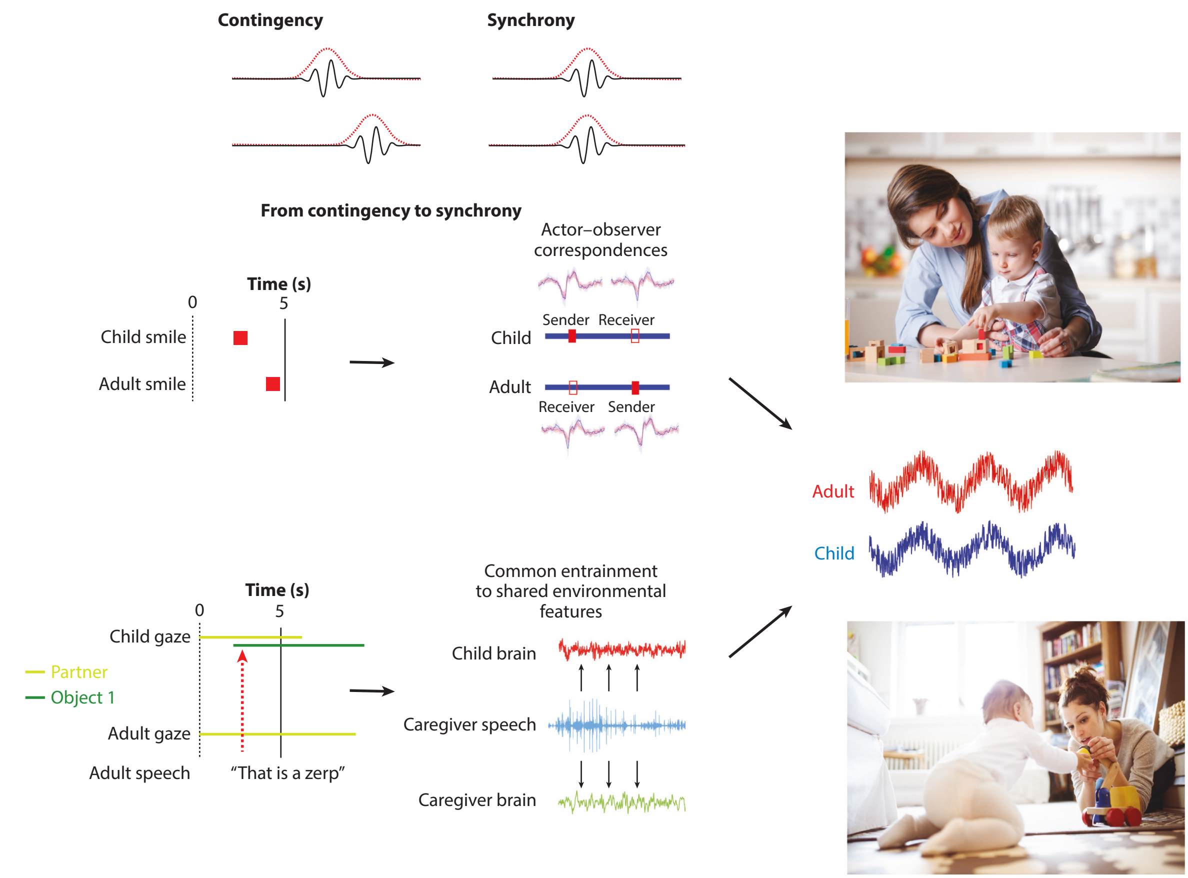

Figure 3

Schematic illustrating the pathways from contingency to neural synchrony, as discussed in Section 5.

In Section 4, we describe cases in which social contingency leads to moments where behavioral processes co-occur in time across modalities (e.g., an infant's gaze and a caregiver's decision to label an object). Beyond this, though, are there mechanisms through which fine-grained brain synchrony might increase that are not directly tied to onsets of concurrent behavior? And does this also facilitate learning? One idea is attention-enhanced synchrony: We know that paying attention to something such as natural speech leads to increases in stimulus–brain synchrony (Poeppel & Assaneo 2020). If two individuals are paying attention to the same information at the same time, this leads to concurrent patterns of brain activity and synchrony (Burgess 2013). Second, we know that there is evidence for motor-induced neural synchrony during actor–observer correspondences: Similarities in brain activity between watching a partner perform an action and performing it oneself (Kingsbury et al. 2019) may also cause neural synchrony to occur in the absence of behavioral synchrony (Hamilton 2021). For example, Ménoret and colleagues (2014) identified markers of social interactions by synchronizing an electroencephalogram (EEG) to the onset of the actor's movement. Concurrently, a suppression of beta oscillations was rapidly observed in the actor's EEG and the observer's EEG after the onset of the actor's movement.

Both of these processes, common entrainment to external environmental features and actor–observer correspondences, would give rise to temporally synchronous patterns of brain activity across multiple timescales and brain regions (Redcay & Warnell 2018, Simony et al. 2016) (see **Figure 3**). Based on current evidence, though, it remains unclear whether this brain synchrony is best viewed as an observable result of social interactions (i.e., a correlate of effective learning that has no direct causal role) or as a core mechanism underpinning them (i.e., something that itself causally improves learning) (Novembre & Iannetti 2021).

If synchrony is to be viewed as a core mechanism, then one process that might mediate this is variability in phasic sensitivity, contingent on the cycle of underlying oscillatory activity. This has the potential to facilitate learning since research in adults has shown that the phase of neural oscillations at the time of stimulus presentation may relate systematically to the excitability of neural populations and to the magnitude of event-related responses (Busch et al. 2009, Mathewson et al. 2009; but see Ruzzoli et al. 2019). Accordingly, perceptual stimuli that are delivered during a high excitability oscillatory phase may be more likely to be detected and encoded than stimuli that arrive at an inhibitory oscillatory phase (Busch et al. 2009, Mathewson et al. 2009). During an interaction, a transient state of entrainment may develop, which helps to ensure that high excitability oscillatory phases co-occur for the duration of the existence of a high-synchrony state. This, in turn, may help to ensure that the sender of information (such as word labels) can present that information at optimal phases for encoding by the receiver (Wass et al. 2020).

As yet, though, this hypothesis remains untested. Evidence that fine-grained neural coordination (either phase synchrony or Granger-predictive relationships) develops during a free-flowing infant–caregiver interaction is actually relatively weak, and early findings that Granger-predictive relationships are increased during mutual gaze (Leong et al. 2017) have failed to replicate (Marriott Haresign et al. 2023). Although a number of important papers have reported different aspects of neural synchrony to occur more frequently than chance (Nguyen et al. 2020a,b; Piazza et al. 2020; Santamaria et al. 2020), significant challenges remain in considering the potential contribution of behaviors and behavioral artifacts (Marriott Haresign et al. 2024). To demonstrate that neural synchrony is a core mechanism, multibrain stimulation studies seem crucial (Novembre & Iannetti 2021). These have been conducted, but results so far are mixed (Novembre et al. 2017, Pan et al. 2021, Szymanski et al. 2017).

In sum, then, contingency leads to the synchronicity of behavior both across modalities (e.g., I look at an object and in response you provide the verbal label for what I am looking at) and within modalities (e.g., I smile and you smile back). Both forms of temporal coordination may cause temporally co-occurring patterns of brain activity via shared entrainment to environmental cues and actor–observer correspondences. Temporal coordination across modalities may allow caregivers to present new information at a time when an infant is optimally sensitive to receiving it, thus maximizing the effectiveness of learning exchanges. But there is currently no strong evidence that brain–brain synchrony plays a causal role in learning, beyond the fact that it constitutes a marker of modally contingent and synchronous social interactions.

6. ATTENTIONAL PATHWAYS TOWARD INTENTIONAL COMMUNICATION

Above, we mostly describe strategies that caregivers use to bootstrap their infants' attention. But over time, unilateral coregulation (where the caregiver adapts to the child more than vice versa) gradually gives way to a more symmetrical coregulation, when caregiver and child both contribute to the ongoing interactions (e.g., Aureli et al. 2022, Bakeman & Adamson 1984, Evans & Porter 2009, Fogel 2018, Perapoch Amadó et al. 2023b). In this section, we focus on how infants learn to direct their caregivers' attention voluntarily and how this paves the way for communicative development. When do infants start using gaze behaviors to intentionally communicate their interest to others and to proactively engage them in attention sharing? How do they discover the

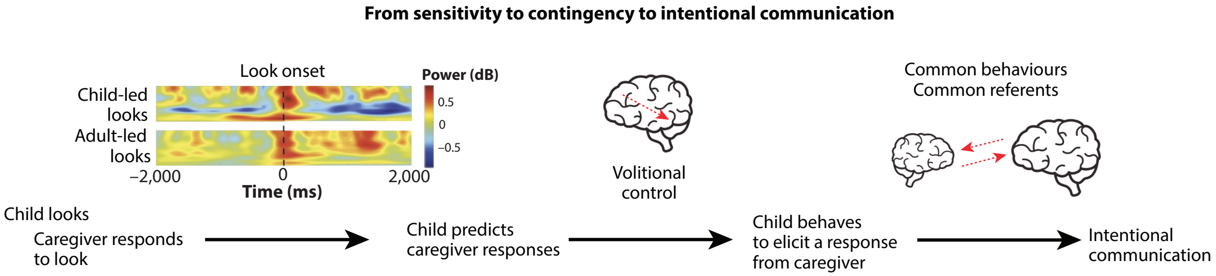

Figure 4

Schematic illustrating the arguments of Sections 4–6, showing the possible developmental influences between interpersonal contingencies, predictive brain mechanisms, volitional control, and intentional communication.

principles that govern conventional communication, including the referential nature of words and the fact that communication works only when interlocutors share a common body of knowledge to which they can refer in turn? It turns out that the answers to these questions involve the two interactional parameters we have discussed thus far: contingency and resulting synchrony (see **Figure 4**). By impacting infants' attention, contingency and synchrony also bootstrap the emergence of intentional and conventional communication through at least three interdependent and cumulative attentional pathways.

The first pathway relies on a process of internalization. To understand the principles behind intentional communication, infants must learn that producing certain behaviors typically induces specific responses in their interlocutors (see Section 4). An influential view has been that intentional communication develops through a four-step process of internalization (Bruner 1974, Vygotskij 1979) (note that these ideas are relatively compatible with the neurocomputational associative accounts we describe in Section 4). This type of model has been used to explain how infants learn to use pointing (Begus & Southgate 2018, Kidd & Holler 2009, Kovács et al. 2014, Wu & Gros-Louis 2014) and vocalizations to communicate (Elmlinger et al. 2023, Ghazanfar & Zhang 2016, Gros-Louis et al. 2006, Wass et al. 2022). Can it also explain the emergence of intentional communication through gaze? Internalization follows the following steps. (*a*) Infants start by producing specific behaviors (e.g., gaze shifts toward objects), but these behaviors are not communicative yet. They are initially cues, in biological signaling theory terms (Smith & Harper 1995); although they may provoke specific responses in receivers, they are not designed to do so. In Section 2 we describe evidence suggesting that this initial step exists: Early on, infants' gaze shifts are largely unpredictable and unconnected to the behaviors or their social partners. (*b*) Caregivers respond to infants' behaviors consistently (see Section 4). (*c*) Infants can register these contingencies between their behavior and caregivers' responses, which allows them to progressively learn to predict caregivers' responses as a function of the type of behaviors that they produce themselves (see Section 4). (*d*) Equipped with these predictive models, infants can then start to voluntarily produce specific behaviors to proactively direct their caregivers' attention. At this stage, these behaviors become genuine communicative signals: behaviors that function to produce a specific response in a receiver. They also become intentional: Infants produce them with the intention of provoking a response in receivers.

Intentional gaze communication of this sort might already manifest when 5- or 6-month-old infants start actively alternating their gaze between a specific target and their caregivers' face (Striano & Bertin 2005), but the clearest signs of this appear toward the beginning of the second year of life, when infants start using gaze as a function of others' attentional focus and alongside other communicative signals such as pointing or vocalizations (Donnellan et al. 2020, Moore &

D'Entremont 2001, Wu & Gros-Louis 2014) or requesting help (Bazhydai et al. 2020, Goupil et al. 2016).

Overall, the evidence reviewed in Section 4 supports the idea that the communicative potential of gaze shifts is progressively internalized by infants thanks to social contingency. In this view, gaze is important for communicative development because—alongside pointing and vocalizations—caregivers' contingent responses to infants' shifts in visual attention allow them to understand that these behaviors can be used to evoke responses in receivers. Behavior across other modalities, such as touch and physical positioning, may show a similar transition from being produced unconnected to the behaviors of their social partners to being produced proactively to direct their caregivers' attention, with the importance of one modality over another potentially differing between social settings; unfortunately, these modalities remain underresearched.

The second and third attentional pathways pave the way for conventional communication learning more specifically by supporting infants' discovery of two of its key properties: its reliance on symbols that arbitrarily refer to specific meanings by convention and, relatedly, the importance of common knowledge for communication. The second attentional pathway concerns the process through which social contingency supports infants' discovery of the referential nature of speech. Much research has been dedicated to this issue, and it has been recently reviewed elsewhere (Luchkina & Xu 2022, Masek et al. 2021), so we discuss it only briefly here. A large body of research suggests that caregivers' tendency to name objects contingently on their children's attentional focus, which we discuss in Section 4, also helps children to learn word meanings because it connects words with specific events or objects both spatially and temporally (Goupil et al. 2024, Tamis-LeMonda et al. 2001, Tomasello & Farrar 1986, Yu & Smith 2012). This can play two interrelated roles. First, it highlights the functional role of words as communicative devices. Similar to what we describe above concerning gaze communication, when parents use words immediately after their infant looks toward a specific object or event, they make the causal link between their utterance and the child's gaze shift manifest by virtue of the temporal priority principle (Hume 1896). A large body of research suggests that repeatedly experiencing such a connection allows infants to understand the referential nature of language (Luchkina & Xu 2022, Masek et al. 2021; see also Section 4). Second, contingent naming reduces referential ambiguity: When a novel label occurs at a time when an infant is already focusing their attention on something, the number of potential referents they could link to this word is greatly reduced as compared with when naming occurs outside of these episodes (Pereira et al. 2014, Vong et al. 2024).

Third, both social contingency and synchrony support the establishment of genuinely shared attention episodes, which have long been described as key events for communicative development, notably because they can help establish common knowledge between interactive partners (Tomasello 2014). By supporting a common reference, shared attention offers a window into the minds of others: When partner A and partner B are both looking at X, and if they both recognize that they are both attending to X (e.g., by mutually monitoring each other's focus of attention) (Siposova & Carpenter 2019) and acknowledge that this is the case (e.g., by smiling or looking toward each other), and provided that they know that seeing leads to knowing (something toddlers seem to typically understand during the course of their second year) (D'Entremont & Morgan 2006, Moll & Tomasello 2007), they can both infer that their partner is also thinking about X and that they are doing this together. It is only once such a symmetrical mode of interaction is achieved that infants and caregivers can be said to truly engage in shared attention.

Importantly, when partner A's and partner B's foci of attention become shared in such a way, they can then notice things about X together, such as its position, color, shape, and so on. These observations become common ground between them and can support their future exchanges about

X. Therefore, once infants are able to direct their partners' attention to objects or events (e.g., using the first attentional pathway we described), they can effectively start taking an active part in protoconversations by selecting suitable topics.

7. APPLICATIONS, FUTURE DIRECTIONS, AND CONCLUSIONS

Social interactions are like a dance. Like any dance, they are defined by temporal interdependencies: How the system changes between time x and time $x + t$ is contingent on the state of the system at time x (Bergson 2007, Cole et al. 2020). And they are relational in essence: The change in partner A is contingent not just on the previous state of partner A but also on the state of partner B (Bales et al. 2023, Fogel 1993, Schneirla 1946). It is this dance that drives infants' attentional and cognitive development as it progressively elaborates and unfurls, encompassing levels of explanation that become greater, more varied, and epistemologically more complex over time.

Just like any dynamical system, disruption to any aspect of the system during early development can lead to cascading effects that manifest over a progressively wider range of different developmental domains (Gottlieb 1991, Johnson 2015, Karmiloff-Smith 1998, Tamis-LeMonda 2023, Thelen 2005). For example, early sensorimotor skills are considered foundational in driving the development of goal-directed attention and intentional behavior. Because causal pathways are so intertwined, both between developmental domains within an individual (Karmiloff-Smith 1998) and across relationships between individuals (Wass et al. 2024), they can be hard to disentangle.

In theory, our approach of studying how social interactions shape the development of attention and how this in turn impacts the emergence of infants' discovery of intentional communication means that, when development is following an atypical trajectory, interventions that target atypical interactional dynamics ought to move development back toward its normal course. If an approach that construes attentional development as a form of maturation that depends on the growth and reorganization of specific brain structures might view atypical development as predestined, then an approach that emphasizes how early experiences drive cognitive development ought to emphasize that early atypical development is amenable to intervention to change its course.

In practice, though, while it is often possible to identify when early child–caregiver interactions are atypical, identifying the reasons why they are atypical can be challenging. It can be hard to differentiate active environmental influences on developmental psychopathology (e.g., more anxious caregivers interacting differently with their children and these interactional differences causing increased rates of psychopathology in the child) from passive genetic linkage (e.g., shared genetic influences causing the co-occurrence of symptoms of psychopathology in families) (Ahmadzadeh et al. 2019, Aktar et al. 2019, Cheesman et al. 2020). This is particularly true because children and caregivers are often phenotypically related, meaning that environmental variability and genetic variability are interdependent.

Because child–caregiver dyads operate as a single, interacting system, atypicalities in one member of the dyad are often compensated for by atypicalities in the other. Children can underinitiate (Forcada-Guex et al. 2006), caregivers can overlead (Feldman 2006), children can be underresponsive (Grzadzinski et al. 2021, Wan et al. 2019), and caregivers can be either overresponsive (Beebe et al. 2016) or underresponsive (Bernard et al. 2018). But over time, the members of a dyad adaptively recalibrate to one another (Fogel 2018, Parrinello & Ruff 1988) such that atypical behaviors in one partner lead to the emergence of atypical behaviors in the other partner over time. For example, during triadic interactions, caregivers of infants at elevated likelihood of developing autism produce utterances with more directive content (Woolard et al. 2021), show fewer contingent responses to their infants' vocalizations (Edmunds et al. 2019), and receive lower overall ratings of responsivity on global rating scales assessing caregiver sensitivity (Wan et al. 2012). But these atypicalities may be a consequence, or a cause, of earlier-emerging atypicalities in the child's behavior.

Overall, evidence from intervention research suggests that interventions that target one member of the dyad individually can affect child–caregiver coregulatory dynamics (Kaaresen et al. 2006) and that interventions targeting child–caregiver coregulation can affect symptoms in each member of the dyad alone (Smith et al. 2022), with some exceptions (Spittle et al. 2015). These findings are expected based on the framework we have laid out in this article. Relatively little research, however, has specifically examined how targeting parent–child interactions can affect cognitive development in the child (Feldman et al. 1999). Investigating this further should be an aim for future research.

At the neural level, there also remains considerable work to be done in investigating how children's brains learn to predict caregivers' responses. Our understanding of the neural mechanisms through which predictability during early social interactions influences long-term brain development remains relatively rudimentary (Glynn & Baram 2019, Köster et al. 2020, Ward et al. 2023). At the moment, we also understand relatively little about the neural mechanisms that we discuss in Section 2, through which multimodal inputs from caregivers influence the development of attention and attractor states, and about how short-term moment-by-moment influences transition toward long-term effects.

At the conceptual level, there also remains important work to be done in investigating what level of contingency is optimal. In this article we examine how the presence of temporal coordination between caregiver and child drives child development. But other research, from both experimental studies and clinical observations (Ham & Tronick 2009, Mitsven et al. 2022, Smith et al. 2021), suggests that optimal development may involve the presence of coordination that is present some of the time, but not always.

There is also considerable work to be done in understanding neural synchrony. At the moment, most research tends to view neural synchrony as an on-off phenomenon (Marriott Haresign et al. 2024), predicated on the idea that better development associates with infants and caregivers being more in sync. In reality, we have 10^{15} synapses per brain, and the current measures that we use to measure temporal coordination across interacting brains look at timescales that vary from milliseconds to hours and measure the coordination of phase, amplitude, and power using measures that do not themselves interrelate (Marriott Haresign et al. 2024). The word synchrony encompasses a range of different types of temporal coordination, between different areas of the brain and across different timescales. Understanding this is crucial if we are to discover whether neural synchrony is an upstream cause or merely a downstream correlate of contingent communication.

Our starting point for this article is the epistemological divide between two theoretical traditions in developmental science: on the one hand, theories that construe attentional development as the product of maturation that depends on the growth and reorganization of specific brain structures and, on the other hand, theories that consider that attention is constructed through social experiences accrued during interactions with other agents. Our aim is to show the mechanisms through which social interactions can drive development and that are more traditionally accounted for in terms of maturation, growth, and reorganization in the brain. Specifically, we have examined how social interactions shape the development of an infant's capacity to pay attention while on their own and, through that, their ability to track mental states in others.

We hope that we show that our opening quotation from Gibson, which was written with just one individual in mind, applies equally well as a description of how development takes place in the space between two interacting individuals. When interacting with our partners, we use perception to move, and we use movement to perceive.

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