

Contingency and synchrony: interactional pathways towards attentional control and intentional communication

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## Abstract

In this article we examine how contingency and synchrony during infant-caregiver interaction helps children to 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 specialised 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 behaviour. Finally, we discuss how contingency and synchrony of brain and behaviour can drive children's ability to direct their caregivers' attention voluntarily; and how this, in turn, paves the way for intentional communication.

## Keywords:

Contingency, synchrony, co-regulation, self-regulation, attention control, communication, intentional

## 1 Introduction

“We must perceive in order to move, but we must also move in order to perceive”

(Gibson, p.223, 1979)

We spend the majority of our early 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 as they appear and disappear on-screen, or to an experimenter performing a specific activity (e.g. (Orehova 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 behaviours such as “look duration”, “number of fixations”, “resistance to the distractor”, etc., change not only over developmental time but also under different situations and neurodevelopmental disorders

(Cohen, 1972; Colombo & Cheatham, 2006; Forest & Amso, 2023; Hendry et al., 2019; Johnson et al., 1991).

Over the past decade, increasing efforts have been made to take a different approach, by researching instead how children spontaneously deploy and structure their attention in real-world settings during unconstrained free behaviour with their caregiver (e.g. (Abney et al., 2020; Franchak et al., 2018; Le et al., 2021; S. V. Wass et al., n.d.; Yu & Smith, 2013, 2016)). This approach is allowing us to study a variety of important features of attention that lab-based experimental studies are unable to capture. For example, during free behaviour, infants' attention durations are longer towards objects that they attend to jointly with other people, compared to on their own (Yu & Smith, 2016). Caregiver behaviours influence the durations of individual attention episodes moment-by-moment (Bakeman & Adamson, 1984; McQuillan et al., 2020; Phillips, Goupil, Whitehorn, Bruce-Gardyne, Csolsim, Kaur, et al., 2023; S. E. 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 reorganisation of specific brain structures (Colombo & Cheatham, 2006). On the other hand are theories that consider that attention is constructed through experiences, in particular social experiences accrued during interactions with other agents (Fogel & Garvey, 2007). Here, we try to bridge the gap between these two traditions by showing how social interactions shape the development

of an infant's capacity to pay attention to objects and things around them in solo settings during later life. In addition, we also discuss how social interactions can influence a child's developing capacity to direct their caregiver's attention voluntarily, to communicate their interest to others and proactively engage them in attention sharing; and, from there, their discovery of the principles that govern conventional communication, including the referential nature of words. 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 characterise early child-caregiver interactions as primarily asymmetric, driven by caregivers dynamically and adaptively changing their own behaviours contingent 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 behaviour, 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 behaviour across modalities, and how this can lead to brain synchrony independent of behavioural synchrony, with possible impacts on attention. In section 6 we discuss how these two interactional parameters - contingency and synchrony - also support their discovery of intentional communication by fostering infants' attentional development. Finally, 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 emphasised 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 signalling to directly and didactically scaffold their child's attention, for example by building a structure of how they pay attention and when, 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 emphasise a one-way flow of information from adult 'sender' to a child 'receiver' (Csibra & Gergely, 2009).

More recent research that examined infant attention in real-world settings during free-flowing infant-caregiver interactions, has, though, 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 (Amadó et al., 2023; Goupil et al., 2023; Phillips, Goupil, Whitehorn, Bruce-Gardyne, Csolsim, Marriott-Haresign, et al., 2023; 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 also found no evidence that 11-month-old infants' brain activity is sensitive to a caregiver's initiation of mutual gaze during play (Marriott Haresign et al., 2023). In comparison to the clear and repetitive stimuli presented in experimental paradigms during free-flowing interactions, ostensive signals are generally rapid, unpredictable, and non-contiguous (Fogel & Garvey, 2007); and potentially, therefore, difficult to track during real-world interactions (Yu & Smith, 2017). These and other recent findings (Çetincelik et al., 2022; Menn et al., 2022; Tan et al., 2022) are giving rise to a theoretical shift away from approaches that emphasise infants' inbuilt sensitivity towards social signals, in particular eye gaze signals, during early attentional development, towards an approach that emphasises the role of culturally situated social interactions and embodied explorations in driving the development of attention (S. E. Schroer & Yu, 2022; Suarez-Rivera et al., 2019; Yu & Smith, 2013).

At birth, attention is believed to be 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, 2-3 times per second (S. Wass, 2022). When 2-14-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 behaviours 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 behaviour in 1-month-olds but was less accurate at reproducing behaviour 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 et al., 2002; S. V. Wass et al., n.d.). 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 behaviours contingent on the child, and that children adapt their behaviours contingent on the caregiver (Beebe et al., 2016; Cohn & Tronick, 1988; Feldman et al., 1999; Murray et al., 2016; Yu & Smith, 2016). But, particularly during early infancy (Beebe et al., 2016; Perapoch Amadó et al., n.d.), the interdependencies between infants and caregivers are relatively more asymmetric: caregivers adapt their behaviours contingent on the child more than *vice versa* (Beebe et al., 2016; Phillips, Goupil, Whitehorn, Bruce-Gardyne, Csolsim, Marriott-Haresign, et al., 2023). And the same finding has also been shown in studies that measure physiology and neural activity, too. 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 behaviours, as we will discuss in section 4) (S. V Wass et al., 2019); see also (Phillips, Goupil, Whitehorn, Bruce-Gardyne, Csolsim, Marriott-Haresign, et al., 2023). And, whereas vocal behaviour in 12-month-olds is heavily contingent on their



own autonomic arousal state, caregivers' vocal behaviour towards infants is more contingent on their infant's autonomic state than on their own (Amadó et al., 2023).

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, they 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 children's attention is re-engaged, they may downregulate their salience (Phillips, Goupil, Whitehorn, Bruce-Gardyne, Csolsim, Kaur, et al., 2023). Together, these findings suggest that, early in development, caregivers dynamically change their own behaviours moment by moment contingent on the attentional state of their child, targeting low-level attention capture to engage their attention. Infants, in contrast, rarely modulate their own behaviours contingent on the attention state of the caregiver.

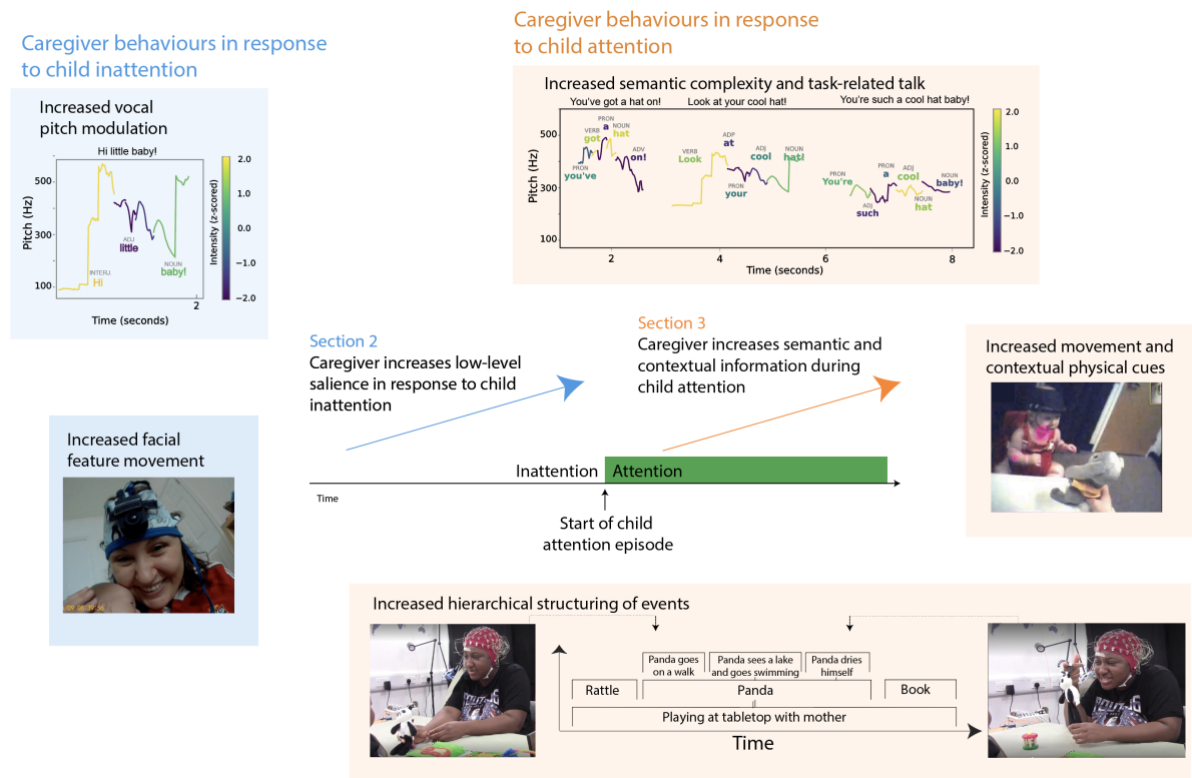


Figure 1: Schematic illustrating caregiver behaviours in response to child inattention (section 2), and caregiver behaviours in response to child attention (section 3)

### 3 'You've caught me, now try to keep me' - semantic and contextual cues, comprehension, and sustained attention

So far, we have considered 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 behaviours 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.

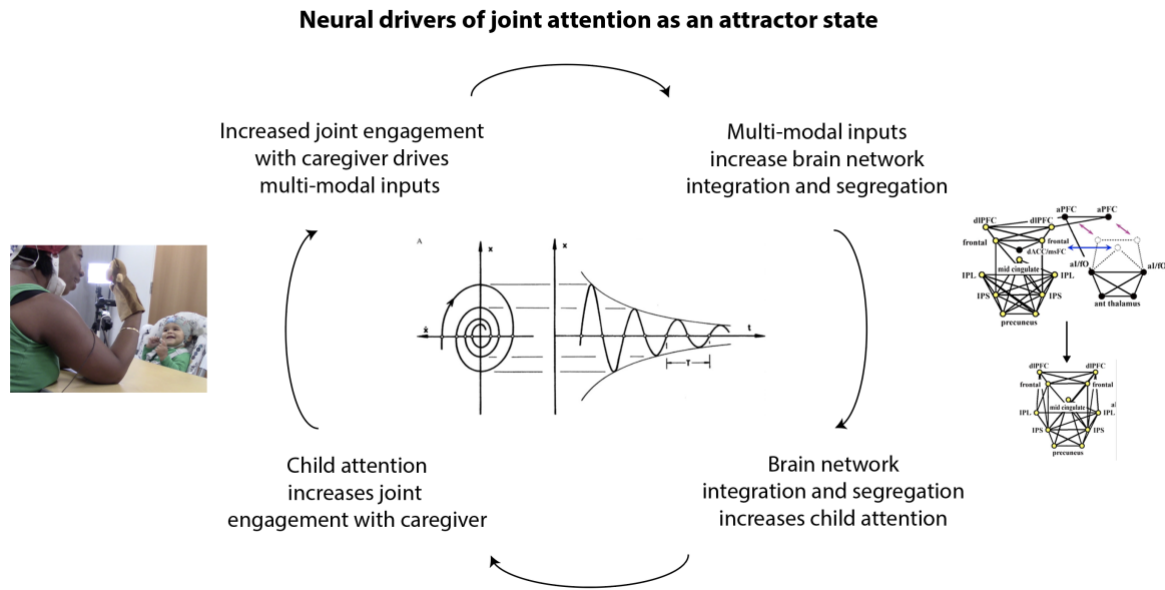
In this section we discuss how caregivers use higher-order features of the interaction, such as semantic and contextual cues, to sustain a child's attention after it is engaged. We also discuss the possible neural mechanisms through which, by providing additional semantic and contextual information during 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; S. V. 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 (S. V. Wass et al., n.d.; S. V. Wass et al., 2018; Yu & Smith, 2016). By following infants' attention patterns, and selectively responding to their cues, caregivers amplify this by prolonging infants' attention states (see Figure 1). To use language from dynamic systems theory, caregivers help contribute towards establishing and maintain short-term attention states as attractors (see Fig 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 (S. Schroer et al., 2019; S. E. 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 towards objects in the short term (Baldwin & Markman, 1989; Belsky, 1980; Carvalho et al., 2019;

Vales & Smith, 2015), and that how caregivers support and scaffold child attention predicts their 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 (S. V. Wass et al., n.d.). These approaches view attention as a product of local cortical interactions which mutually reinforce one another through inter-areal connectivity (Buschman & Kastner, 2015). Recent fMRI 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 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 behavioural performance (van Kempen et al., 2021). Multi-modal cues (such as accompanying a child's gaze towards 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 Fig 2).



*Figure 2: Schematic illustrating neural drivers of joint attention as an attractor state, as discussed in Section 3*

A second strategy consists in acting on the object that is currently attended 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 attention engagement (McQuillan et al., 2020; Sun et al., 2024; Yu & Smith, 2016). Just as caregiver speech increases around object attention, adult's hand actions also markedly increased where infants followed their partner's attention towards an object (Custode & Tamis-LeMonda, 2020; Franchak et al., 2018; Yu & Smith, 2017). In both cases, a child paying attention to an object triggers caregiver behaviours that further amplify the child's attention.

A third, potentially important but under-explored 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 (S. E. Schroer & Yu, 2021) (where the higher order goal is to build a tower, and the nested sub-goal is to find the right 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 sub-goals 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 behaviours 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 behaviours 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, etc. This remains under-studied 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 described in section 2, infants' behaviours are largely unpredictable and unconnected to the behaviours of their social partners, whereas adults are more likely to change their own behaviours contingent on the child. Some child behaviours 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 behaviour.

We know, first of all, that infants are behaviourally and neurally sensitive to when an adult responds contingently to their behaviours (Phillips, Goupil, Whitehorn, Bruce-Gardyne, Csolsim, Marriott-Haresign, et al., 2023; Rayson et al., 2019). In free-flowing tabletop play, 12-month-old infants do not consistently use their gaze or vocalise before an infant-initiated mutual attention episode; but they do show differential neural responses to when a caregiver responds contingently to their initiations by following the child's attentional focus (Goupil et al., 2023; Phillips, Goupil, Whitehorn, Bruce-Gardyne, Csolsim, Marriott-Haresign, et al., 2023). By following a child's initiation, caregivers also prolong the child's attention (Phillips, Goupil, Whitehorn, Bruce-Gardyne, Csolsim, Kaur, et al., 2023; Phillips, Goupil, Whitehorn, Bruce-Gardyne, Csolsim, Marriott-Haresign, et al., 2023). 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., non-contingently), infants' visual attention durations immediately decrease (Mason, 2018; Miller & Gros-Louis, 2013).

Importantly, though, adults are selective in which behaviours they respond contingently to, and which they do not. For example, in joint object play with 9-12-month-olds, caregivers respond more often to mature speech-like vocalisations and vocalisations 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 behaviours will, and which will not, elicit a caregiver response (L. B. 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, based on the associations between active motor behaviours and incoming sensory information (Clark, 2013; Friston, 2019; Köster et al., 2019).

Supporting this perspective are studies that examined change in volitional infant behaviours during free-flowing infant-caregiver interactions, as a function of the frequency and the form of contingent maternal responses. For example, Bigelow and Power 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 (Bigelow & Power, 2016). In joint play interactions, the degree to which a caregiver responds contingently to infant vocalisations at 8 months predicts the number of



directed vocalisations made by infants towards objects at 14 months (Wu & Gros-Louis, 2014). Experimental paradigms have also shown that infants increase behaviours such as the rate of their pointing where an adult consistently provides information contingent on the focus of the infants' gesture (Begus & Southgate, 2012; Kovács et al., 2014).

As well as reinforcing specific infant behaviours, contingent semantic responses by caregivers to re-orientations 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 and Smith showed that 18-month-old infants learnt object labels better at moments where the adult labelled an object in the time when they were looking towards that object (Yu & Smith, 2012). Goupil and colleagues have since replicated this finding in a table-top play setting with 14-month-old-infants (Goupil et al., 2023).

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 seconds before infants led a shared attention episode towards an object, compared to where they followed their caregiver's look (Goupil et al., 2023). Behavioural signals, such as a child initiating an attention shift towards an object, or 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 et al., 2015; Begus & Southgate, 2018; Goupil et al., 2023). This signalling allows caregivers to present new information at a time when an infant is optimally sensitive to receive it, thus maximising

the effectiveness of learning exchanges. Over time, infants come to expect to receive information in the time after they re-orient their behaviour during shared interaction, based on past experiences of information being provided contingent 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 behaviour that involve redirecting their partner contingent 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 forwards-predict changes in partner B. Contingency is directed ( $A \rightarrow B$  is not the same as  $B \rightarrow A$ ). Synchrony, in contrast, is a concurrent relationship: when partner A is high (or low), partner B is low (or high). Synchrony is, therefore, undirected ( $A \rightarrow B$  is the same as  $B \rightarrow A$ ) (see Figure 3).

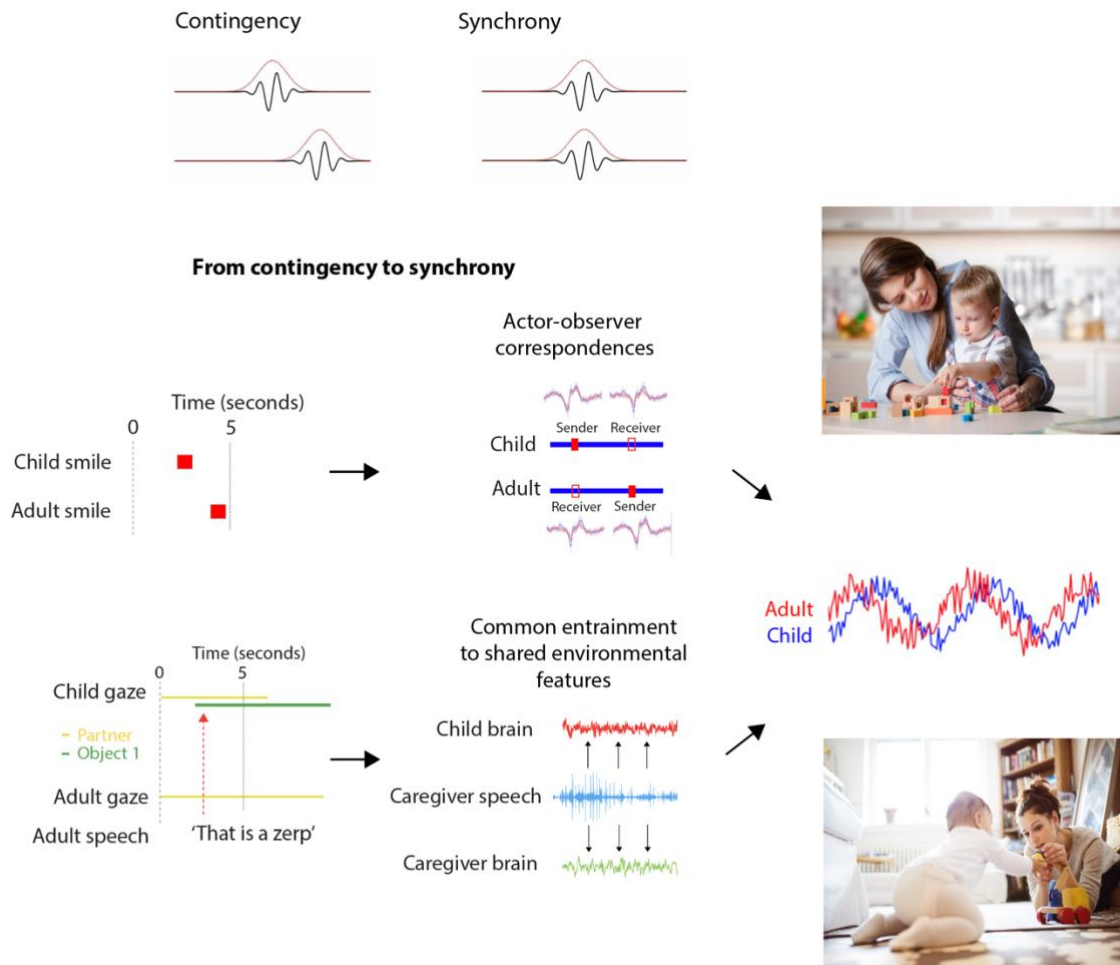


Figure 3: Schematic illustrating the pathways discussed in Section 5, illustrating pathways from contingency to neural synchrony

In effect, though, 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 behaviour 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 which 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 behavioural state at the same time. The second is where contingency causes actors to be in the same behavioural state at the same time (e.g. I smile at you and you smile back).

In section 4, we have described cases where social contingency leads to moments where behavioural processes co-occur in time across modalities (e.g., an infant gaze and a caregivers' 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 behaviour? And does this also facilitate learning? One idea is of 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 behavioural synchrony (Hamilton, 2021). For example, Ménoret and colleagues identified markers of social interactions by synchronising EEG to the onset of the actor's movement (Ménoret et al., 2014). Concurrently, a suppression of beta oscillations was observed in the actor's EEG and the observer's EEG rapidly 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 time-scales 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 which itself causally improves learning) (Novembre & Iannetti, 2021).

If it 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 as 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) (although 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 during an interaction which helps to ensure that, for the duration of the existence of a high synchrony state, high excitability oscillatory phases co-occur. 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 (S. V 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 interactions 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 be above chance (Nguyen, Banki, et al., 2020; Nguyen, Schleihau, et al., 2020; Piazza et al., 2020; Santamaria et al., 2020), significant challenges remain in considering the potential contribution of behaviours and behavioural artifact (Marriott Haresign et al., pre-print). To demonstrate that neural synchrony is a core mechanism, multi-brain stimulation studies seem crucial (Novembre & Iannetti, 2021). These

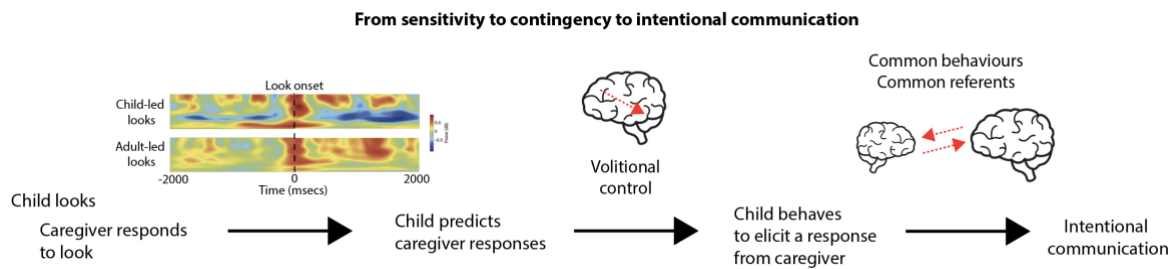
have been conducted, but results so far are mixed (Novembre et al., 2017; Pan et al., 2021; Szymanski et al., 2017).

In sum, then, contingency leads both to the synchronicity of behaviour 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 receive it, thus maximising 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 towards intentional communication.**

So far, we have mostly described 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 co-regulation", when mother and child both contribute to the ongoing interactions (e.g. (Aureli et al., 2022; Bakeman & Adamson, 1984; Evans & Porter, 2009; Fogel, 2017; Perapoch Amadó et al., n.d.)). In this section, we focus on how infants learn to direct their caregivers' attention voluntarily, and how this paves the way for communicative development. We ask: when do infants start using gaze behaviours to intentionally communicate their interest to others and to proactively engage them

in attention sharing? How do they discover the principles that govern conventional communication, including the referential nature of words, and the fact that it only works when interlocutors share a common body of knowledge to which they can refer in turns? It turns out that the answers to these questions have to do with 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.



*Figure 4: Schematic illustrating the arguments of sections 4-6*

The first pathway relies on a process of internalisation. To understand the principles behind intentional communication, infants must learn that producing certain behaviours 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 internalisation (Bruner, 1974; Vygotskij & John-Steiner, 1979) (note that these ideas are relatively compatible with the neurocomputational associative accounts we described 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 vocalisations to communicate (Elmlinger et al., 2023; Ghazanfar & Zhang, 2016; Gros-Louis et al., 2006; S. V Wass et al., 2022). Can it also explain the emergence of intentional communication through gaze?

Internalisation follows the following steps: (i) infants start by producing specific behaviours (e.g., gaze shifts towards objects), but these behaviours are not communicative yet. They are initially cues in biological signalling theory terms (M. J. Smith & Harper, 1995): although they may provoke specific responses in receivers, they are not designed to do so. In section 2 we have described evidence suggesting that this initial step exists: early on, infants' gaze shifts are largely unpredictable and unconnected to the behaviours or their social partners; (ii) caregivers respond to infants' behaviours consistently (see section 4); (iii) infants can register these contingencies between their behaviour and caregivers' responses, which allows them to progressively learn to predict caregivers' responses as a function of the type of behaviours that they produce themselves (see section 4). (iv) equipped with these predictive models, infants can then start to voluntarily produce specific behaviours to proactively direct their caregivers' attention. At this stage, these behaviours become genuine communicative signals: behaviours whose function is 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 be manifested when 5/6-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 towards 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 vocalisations (Donnellan et al., 2020; Moore & D'Entremont, 2001; Wu & Gros-Louis, 2014), or to request help (Bazhydai et al., 2020; Goupil et al., 2016).

Overall, the evidence reviewed in section 4 supports this idea that the communicative potential of gaze shifts is progressively internalised by infants thanks to social contingency. In this view,



gaze is important for communicative development because – alongside pointing and vocalisations – caregivers' contingent responses to infants' shifts in visual attention allow them to understand that these behaviours can be used to evoke responses in receivers. Behaviour across other modalities, such as touch and physical positioning, may show a similar transition, from being produced unconnected to the behaviours 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 under-researched.

The second and the 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 will be brief here. A large body of research suggests that caregivers' tendency to name objects contingently on their children's attentional focus, which we have already discussed in sections 4, also helps children to learn word meanings, because it connects words with specific events or objects both spatially and temporally (Goupil et al., 2023; 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. Similarly to what we just described concerning gaze communication, when parents use words immediately after their infant looks towards a specific object or event, they make the causal

link between their utterance and the child's gaze shift manifest in 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); also see 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 to 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 common reference, shared attention offers a window into others' minds: when partner A and partner B are both looking at X, and if they both recognise 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 towards 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 and Bs' foci of attention becomes shared in such a way, they can then notice things about X together, such as its position, its colour, shape, etc. 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 proto-conversations 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 1 is contingent not just on the previous state of partner 1, but also on state of partner 2 (Bales et al., 2023; Fogel, 1993; Schneirla, 1946). It is this dance which 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 sensory-motor skills are considered foundational in driving the development of goal-directed attention and intentional behaviour. Because causal pathways are so intertwined, both between developmental domains within an individual ((Karmiloff-Smith, 1998)) and across relationships between individuals (S. V. 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, then interventions which target atypical interactional dynamics ought to move development back towards its normal course. If an approach that construes attentional development as a form of maturation that depends on the growth and reorganisation of specific brain structures might view atypical development as predestined, then an approach that emphasises how early experiences drive cognitive development ought to emphasise that early atypical development is amenable to intervention to change its course.

In practice, though, while often it is possible to identify when early child-caregiver interactions are atypical, identifying the reasons why this is 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.

And 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 under-initiate (Forcada-Guex et al., 2006), caregivers can over-lead (Feldman, 2006), children can be under-responsive (Grzadzinski et al., 2021; Wan et al., 2019), caregivers can be either over-

responsive (Beebe et al., 2016) or under-responsive (Bernard et al., 2018). But over time, the members of dyad adaptively recalibrate to one another (Fogel, 2017; Parrinello & Ruff, 1988), so that atypical behaviours in one partner lead to the emergence of atypical behaviours 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' vocalisations (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 of earlier-emerging atypicalities in the child's behaviour, or a cause.

Overall, evidence from intervention research suggests that interventions that target one member of the dyad individually can affect child-caregiver co-regulatory dynamics (Kaaresen et al., 2006); and that interventions targeting child-caregiver co-regulation can affect symptoms in each member of the dyad alone (C. G. 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 paper. 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 caregiver's 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 discussed in section 2, through which multi-modal inputs from caregivers

influence the development of attention and attractor states, and how short-term moment-by-moment influences transition towards 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 have examined how the presence of temporal coordination between caregiver and child drives child development. But other research, both from experimental studies and clinical observations (Ham & Tronick, 2009; Mitsven et al., 2022; C. G. 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., pre-print), 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 inter-relate (Marriott Haresign et al., pre-print). The word synchrony encompasses a range of different types of temporal coordination, between different areas of the brain, across different time-scales. 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 was 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 reorganisation 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 has been to bridge the gap between these two traditions, by showing 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 have shown 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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