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ARTICLE

Child Development Perspectives

An integrative model of parent-infant communication development

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Abstract

Communication is commonly viewed as connecting people through conscious symbolic processes. Infants have an immature communication toolbox, raising the question of how they form a sense of connectedness. In this article, we propose a framework for infants' communication, emphasizing the subtle unconscious behaviors and autonomic contingent signals that convey drives, emotions, and a sense of connection, facilitating the formation of primal social bonds. Our developmental model emphasizes the importance of diverse modes of communication and their interplay in social interactions during infancy. The framework leverages three levels of communication—autonomic, behavioral, and symbolic—and their different maturational pathways. Initially, infants' social communication relies on autonomic responses and a dynamic behavioral repertoire, which evolve during the first year of life, supporting the emergence of symbolic communication. This extended communication framework highlights infants' role as proactive communicating agents and allows for tracing communicative developmental cascades back to their origins.

KEYWORDS
autonomic system, communication, infancy

INTRODUCTION

Communication is often considered an intentional, planned set of behaviors designed to relay information (Cherry, 1966). When adults interact socially, their conscious verbal communication is accompanied by a "hidden" unconscious layer of subtle behaviors, as well as a rich set of responses to the autonomic nervous system that enables enhanced emotional perception (Tamietto & de Gelder, 2010), anticipation (Adolphs, 2001), and empathy (Prochazkova et al., 2018). For example, subtle decreases in eye blinking or muscle tension in the forehead convey comfort (Marchak, 2013), and changes in heart rate foster noticeable changes in skin color, such as blushing or turning pale (Kret, 2015)—all of which point to the communicative social value of these autonomic signals.

These autonomic changes elicit a sense of connectedness using automatic mimicry mechanisms (Fawcett et al., 2016) and synchronization (Hoehl et al., 2021). In social interactions, dilated pupils in one person elicit dilation responses in the other and tension evokes tension (Fawcett et al., 2016), fostering a sense of togetherness (Prochazkova & Kret, 2017). Given the importance of these cues for conveying social meaning, including them in models of communication deepens our understanding of intercultural and individual differences in communication and our knowledge of the role of primal communication in developing secure affiliative bonds at the start of life.

The mechanisms that enable mature simultaneous multilevel communication develop gradually during infancy and toddlerhood (Rodriguez, 2022), raising the question of how early primal communication is formed and how it is supported. To understand more thoroughly communication in general and caregiver-infant social interactions in particular, we must consider the role of diverse automatic responses and behaviors and their

Abbreviation: ANS autonomic nervous system

interplay in laying the foundation for symbolic communication bids.

Historically, infants' limited communication behaviors have led canonical theorists to believe that the first weeks of infancy may be depicted as a "blooming, buzzing confusion" (James, 1890, p. 488), showing "hardly any sign of perceiving anything beyond their own body" (Mahler, 1958, p. 77). As developmental scientists learn more, this paradigm gradually shifts to include young infants taking active roles in dyadic communication (Filippetti, 2021; Ludwig & Welch, 2022). Technological advancements facilitate the exploration of young infants' perception and communication using autonomic changes in arousal, as an indicator of both perception (Jackson & Sirois, 2009; Zeng et al., 2022) and attention (Rothbart et al., 2011), to study their communicative value (Kret, 2015). These advances allow researchers to surpass behavioral barriers to understand more fully the mechanisms at the base of social interaction (Geva et al., 2017; Wass et al., 2019). (For the sociodemographic characteristics of the studies reviewed herein, see Table S1.)

With this notion in mind, in this article, we propose an integrative theoretical model for understanding changes in parent-infant communication using three levels of communication: (1) symbolic communication, (2) voluntary and involuntary behaviors, and (3) autonomic responses. We review the development of each level during infants' first year and explore how they affect one another during social interaction with their caregivers, creating complex two-way, contingent, multilevel communication.

THREE LEVELS OF COMMUNICATION IN INFANCY

Level 1: Symbolic communication

Symbolic communication enables people to express intention or meaning through sound or gesture (Gomez, 2007; Mundy & Newell, 2007). Emerging at the end of infants' first year of life (Cohen & Billard, 2018; Orr & Geva, 2015), symbolic communication is thought to rely on cognitive development that allows infants to understand symbolism, action and consequences, and violation of expectancies (Rodriguez, 2022). The neural bases of these emerging abilities depend on the experience and maturation of cortical areas (Ahmad et al., 2023), especially the prefrontal cortex, which receives signals from multiple regions (Grossmann et al., 2010; Kolb et al., 2012). The significant increase in prefrontal functional activity indicating neural maturation aligns with infants' cognitive development (Ahmad et al., 2023; Lemaitre et al., 2021). Developments that occur at around 9 months in reasoning and generalization abilities of sensory input, planning motor responses (Kagan & Herschkowitz, 2006), language, and complex social behaviors (Grossmann, 2013) enable the transition from a reactive behavioral level of communication to a symbolic one.

The ability to perform and understand symbolic communication relies on evolving cognitions and motor skills necessary to perform the gesture in a controlled way (Rothbart et al., 2007), as well as on experiences that create learning opportunities (Malachowski & Needham, 2023). Through mechanisms of parental mentalization, infants' goal-directed behaviors are assigned meaning and interpretation by the parent (Goldstein & Schwade, 2008; Shai & Belsky, 2011), who uses imitation and elaboration to help infants learn their symbolic value (Grienenberger et al., 2005).

A prominent example of this notion is the development in the first year of life of pointing during social interaction as an "elaboration" of reaching attempts (see Figure 1). As soon as they can, infants try reaching for objects in their vicinity, regardless of whether they can reach them (Ramenzoni & Liszkowski, 2016). At 8 months, when infants are alone, their frequency of reaching a desired out-of-reach object decreases, but not when they are with their caregiver or an experimenter, suggesting a social understanding and an early attempt to signal their desire (Ramenzoni & Liszkowski, 2016).

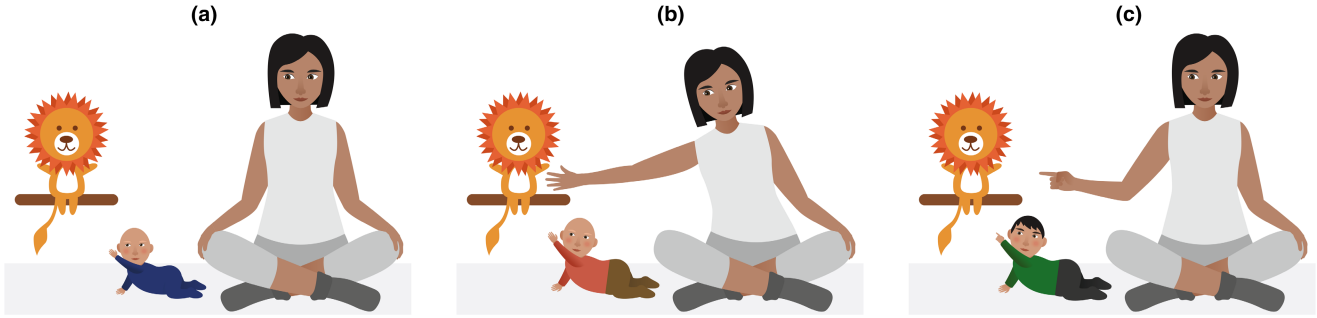

FIGURE 1 The development of pointing during social interaction. The figure shows a schematic representation of the developmental cascade pointing to behavior in the first year of life as an "elaboration" of reaching attempts: (a) infants' behavioral response is trying to reach a desired object in their proximity, (b) caregivers' understanding of infants' signals and desires, and (c) infants' symbolic gesture to signal to their caregivers their desire.

Then, at 9 to 15 months, reaching becomes symbolic in the form of pointing (Carpenter et al., 1998). This process requires intentions (Tomasello et al., 2007), expectations (Carpendale & Carpendale, 2010), and a primal ability of theory of mind (Liszkowski, 2013), as well as joint attention (Mundy & Newell, 2007), and a responsive caregiver who demonstrates pointing and responds to infants' gestures (Ger et al., 2018) based on a pre-existing motor repertoire that is now used to signal a desire or an idea (Geva & Orr, 2016). A similar trend may apply to other symbolic behaviors that emerge from simple behaviors (e.g., aversion communicated by turning their heads away is reconverted to signal "no" by turning their heads away, specific babbling sounds are used to signal verbal ideas resembling heard words).

The transition from motor behavior to a symbolic idea may include a phase of uncertainty in which infants' intentions and meaning are unclear to the receiving agent. During this phase, parents could interpret a behavior as meaningful (symbolic) or meaningless ("just" a motor response). This uncertainty could make it complex to distinguish between symbolic communication (level 1) and behavioral communication (level 2), yet this vague distinction represents the actual interrelations among the three communication levels. Work on parental mentalization (Shai & Belsky, 2011) demonstrates why this phase, which is confusing to define and observe, is crucial for infants' development. The efforts of discerning meaning on the parental side and expressing oneself more clearly on the infants' side are aided by autonomic cues, signaling effort, and importance (Goldinger & Papesh, 2012). Caregivers' ability to deduce implicit information from simple behaviors and understand their infants' state of mind facilitates infants' development of a sense of self and their learning of the symbolic value of behaviors (Camoirano, 2017). Here, we propose a model that highlights the significance of primal behaviors and subtle autonomic cues, infants' primary communicative abilities in expressing symbolic representations and strengthening the caregiver-infant bond.

Level 2: Behavioral communication

From birth, infants use behavior, small movements, and crying to communicate with their caregivers and relay their needs (Farroni et al., 2010; Hym et al., 2021; Shinya et al., 2016). Infants' communicative behaviors can be observed by parents in three domains: (1) *orienting and shifting attention* via head or eye movement (Petersen & Posner, 2012); (2) *emotional expressions* via facial muscle movement and vocal output (Leppanen & Nelson, 2009); and (3) *motor*, namely body movements, changes in muscle tone, posture, and emerging abilities to roll, sit, crawl, and walk (Geva & Orr, 2016).

Infants' ability to use behaviors for communication improves rapidly. Among examples: newborns moving from making small shifts of attention by slight movements of their eyes (Farroni et al., 2010) to an improved ability to follow using head and body movements at 3 to 6 months (Gredeback & Daum, 2015); neonates communicating by crying, then moving to affective expressions by cooing, smiling, and laughing, starting with the social smile at 2 months (Lavelli & Fogel, 2005); and infants being mostly stationary before moving to turning at 4 to 5 months, crawling at 6 months, and standing and walking toward desired targets at about 1 year (Geva & Orr, 2016; Yamamoto et al., 2019). These motor improvements are part of infants' developing communication toolbox, enabling them to relay to their caregivers more effectively their interests (Cohen & Billard, 2018) and emotional states (Prochazkova & Kret, 2017).

Our model highlights the role of infant behaviors preceding symbolic communication during parent-infant interaction when infants form a relationship with their caregivers (Welch & Ludwig, 2017). We suggest that the change in infants' ability to communicate using behaviors improves the ability of their caregivers to understand them and affects infants' internal state. A prominent example of the effect of early behavior on infants' internal state is their ability to use gaze aversion in response to social stimuli (Zeng et al., 2022) or during social interaction (Field, 1981) to cope with over-reactivity (De Schuymer et al., 2012; Zivan et al., 2021); this serves as a primal mechanism of self-regulation (Rothbart et al., 2011), links internal states, and changes behaviors and autonomic responses (Zivan et al., 2021).

Level 3: Autonomic responses

Activity in the autonomic nervous system (ANS) alters multiple physiological processes, such as changes in pupil diameter (Geva et al., 2017; Jackson & Sirois, 2009), heart rate and respiration (Porges & Furman, 2011), and skin conductance that are accompanied by changes in skin color and skin brightness (Kret, 2015). These changes are perceivable, yet they are mostly processed subconsciously (Ludwig & Welch, 2020; Tamietto & de Gelder, 2010), leading researchers to address them as an outcome of interaction (Feldman et al., 2011). In our model, autonomic activity has a communicative value, serving a central role in caregivers' ability to understand their infants and provide them with their basic physical and emotional needs as their affiliative bond forms.

For an autonomic activity to have a communicative value, it needs to be contingent and change as part of social interaction or elicit a social response (Ludwig & Welch, 2020). When two individuals interact, they exchange multiple autonomic responses in milliseconds-seconds (Prochazkova & Kret, 2017), creating a bidirectional feedback loop (Welch & Ludwig, 2017) and causing dyadic changes in arousal levels that facilitate empathy, coregulation, and learning (Ludwig &

Welch, 2020; Prochazkova & Kret, 2017). Indeed, autonomic activity and synchrony are correlated with beneficial and affiliative bonds between caregivers and their infants (Hoehl et al., 2021); however, we suggest that they also play a role in forming them. This extended framework of primal communication integrates the ANS and its communicative value into a three-level mode of operation. The communicative autonomic level of communication is based on primal automatic reflexes, hardwired into the brainstem (Geva et al., 2017; Ludwig & Welch, 2022), that may be partly or fully elusive from conscious perception (Geva & Feldman, 2008), sending and receiving signals through the noradrenergic activity (activity in neural areas related to changes in arousal) via the ANS (Petersen & Posner, 2012).

The ANS matures during gestation (Leppanen & Nelson, 2009) and is a crucial part of the neonatal transition from the womb to the external environment, enabling infants' vital functions, like regular heart rate, breathing, feeding, and maintaining stable body temperature (Mulkey et al., 2021). However, infants still depend on their parents for basic needs (Beebe & Lachmann, 2015; Porges & Furman, 2011). By fulfilling its evolutionary functions, the ANS causes changes in arousal levels (Petersen & Posner, 2012), activating two parallel communication channels, a reciprocal autonomic loop and an autonomic-behavioral loop, designed to ensure that infants' basic needs are met by their caregivers (see Figure 2).

Reciprocal autonomic loop: Infants' ans responses cause changes in caregivers' ans

This form of communication uses an automatic, autonomic mimicry mechanism through direct contact, primarily by skin-to-skin contact, eye contact, or spontaneous physiological synchrony during social interaction (Feldman, 2012), to elicit changes in arousal levels in parents and their infants that enable them to share their arousal state unconsciously (Fawcett et al., 2016), and to synchronize and adapt their behavior to one another (Woodhouse et al., 2020). Physiological synchrony plays a significant role in coregulation processes (Geva & Feldman, 2008; Welch & Ludwig, 2017), increasing feelings of safety and trust that support emotional regulation (Porges & Furman, 2011). The reciprocal autonomic loop is the most primal communication between infants and their caregivers. It starts before birth and becomes fundamental in the first months of life when infants' behavioral abilities are still underdeveloped. For mimicry and synchrony to occur, caregivers must be attentive and engaged, at least at a sufficient level, to receive sensory input from their infants and vice versa (Feldman, 2012; Yarmolovsky & Geva, 2023). When parents are inattentive, infants' arousal increases, creating an attention-getting behavioral response (Zeskind, 2013) and opening the autonomic loop for behavioral communication.

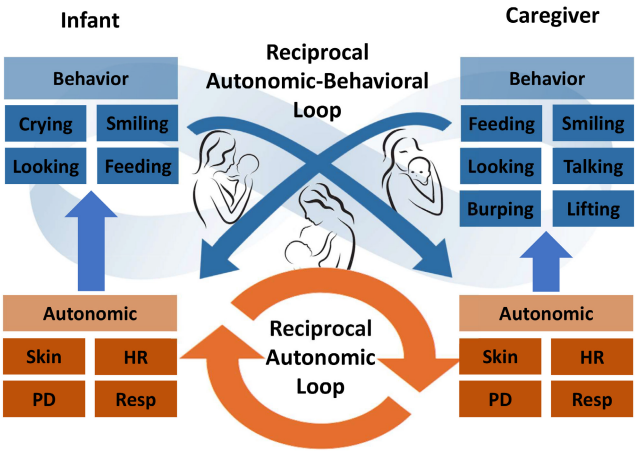

FIGURE 2 The reciprocal autonomic and reciprocal autonomic-behavioral loops. The model shows a schematic representation of communicative autonomic loops: (1) Reciprocal Autonomic Loop (orange). (2) Reciprocal Autonomic-Behavioral Loop (blue). HR, heart rate; PD, pupil dilation; Resp, respiration; Skin, skin conductance/color.

Reciprocal autonomic-behavioral loop: Infants' ans responses cause a behavioral response

Infants can perform a set of behavioral communication signals soon after birth, mainly by crying, cooing, and engaging in bodily movements that may range from smooth and calm to agile and frantic. These behaviors are triggered by arousal changes in response to endogenous evolutionary signals such as hunger, cold, and sleep (Fotopoulou & Tsakiris, 2017). Infants' behavioral response triggers their caregivers' alerting attention network (Petersen & Posner, 2012), leading to parental behavior designed to meet infants' needs (Zeskind, 2013) or calm them using interpersonal social touch (Tanaka et al., 2021), thereby facilitating the return of infants' arousal to baseline. The asymmetric nature of the reciprocal autonomic-behavioral loop enables infants to learn to predict their environment, develop expectations from their surroundings, and form representations of their caregivers (Atzil et al., 2018; Ciaunica et al., 2021). Given the potency and contingency of these cues, available from childbirth or even earlier, they are an integral, interdependent part of young infants' communication toolbox.

MODES OF INTERDEPENDENCY ACROSS COMMUNICATION SYSTEMS

Infants are thought to be born with a relatively mature autonomic system (Mulkey et al., 2021) and some behavioral capabilities (Zeskind, 2013). At first, infants'

primary communication channel is autonomic, combined with raw behaviors designed to provide them with basic modes for expressing needs like feeding, sleep, and warmth (Prochazkova & Kret, 2017). Then, after 2–3 months, infants begin to express their needs and to interact with their surroundings using smiling (Lavelli & Fogel, 2005) and following in a more controlled manner, which changes the nature of the interaction (Gredeback & Daum, 2015). The next step, indicating a change in the interaction mode, happens between 6 and 9 months, when infants begin to use symbolic gestures (Rodriguez, 2022) and joint attention (Mundy, 2018), and can gain distance from their caregivers, taking a much more active behavioral role in the interaction (Hodges et al., 2020).

The ability to communicate at multiple levels continues to evolve as infants mature, and as they expand their communicative repertoire and their ability to relay more complex notions or finely tuned signals about their emotional state (Leppanen & Nelson, 2009) and needs (Cohen & Billard, 2018). New abilities affect infants' communicative skills at the same and other levels. Even though we do not fully understand the interdependency among the three levels of communication, the supposition is that access to greater self-regulation capacities enables acting or inhibiting action while sustaining hyper- or hypo-arousal (Blair & Ursache, 2011; Engel & Gunnar, 2020). Decreased contingency with autonomic activity due to infants' growing ability to contain arousal increases while sustaining a stable behavioral output (Blair & Ursache, 2011; Zeng et al., 2022). Schematically depicted in Figure 3, the newly developed symbolic abilities enable infants to self-regulate and decrease the weight of autonomic signals in altering behavioral output, such as changes in proximity from the parent during dyadic interaction (Rothbart et al., 2011).

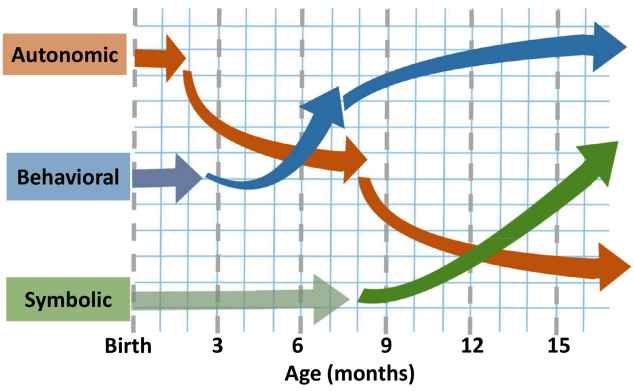

FIGURE 3 Three levels of communication in infancy: a developmental cascade. The model shows a schematic representation of the developmental cascade of the three levels of communication in infancy: (1) the autonomic level (orange), (2) the behavioral level (blue), and (3) the symbolic level (green).

THREE LEVELS OF COMMUNICATION DURING DYADIC CONTINGENT INTERACTION

Along with infants' internal adaptation, parents' ability to adapt and change their behavior according to their infants' behavior is a crucial factor in developing the infant-caregiver bond (Woodhouse et al., 2020). However, we know little about what mechanisms enable caregivers to discern what their infants need and how to adapt before infants develop symbolic communication. During early dyadic interaction, infants and caregivers exchange a series of multilevel contingent responses that could exist in both reciprocal autonomic loops and autonomic-behavioral loops that facilitate learning and perception of the emerging parent-infant bond.

The reciprocal autonomic loop enables caregivers to relay and experience infants' physical and emotional needs, strengthening the physical and emotional bond through reward and learning mechanisms (Beebe & Lachmann, 2015; Feldman, 2012; Feldman et al., 2011; Ludwig & Welch, 2020). The reciprocal autonomic-behavioral loop is unique in highlighting the asymmetric relationship between infants and caregivers, which enables infants to develop expectations from their surroundings (Tanaka et al., 2021), creating a solid representation of the caregiver (Woodhouse et al., 2020). Caregivers' ability to ascribe meaning through mechanisms of mentalization enables infants to begin to organize their internal state, discern themselves from their surroundings, and later use the same signals to express themselves. These, in turn, modify parental representations of the world and alter their predictions based on their infant's growing cognitions and communicative abilities (Gergely & Watson, 1996). The proposed multilevel communication model highlights infants' active role in the interaction and caregivers' unique role in providing the infrastructure for development. Our model joins lines of study that move from traditional frameworks that hold the "good enough mother" responsible for infants' development (Winnicott, 1960, p. 585), highlighting infants' proactive role in dyadic communication even before intention or awareness (Ciaunica et al., 2021; Goldstein et al., 2009; Gros-Louis et al., 2016; Trevarthen & Aitken, 2001; Tronick, 2018).

Caregiver-infant interaction changes and affects caregivers' and infants' internal states (Fotopoulou & Tsakiris, 2017; Hoehl et al., 2021; Leclere et al., 2014). Gaps in the literature limit the development of a parallel developmental cascade framework of parental brain maturation in response to infants' growing abilities. But we know that mature neural networks adapt and change before and after birth in both fathers and mothers (Diaz-Rojas et al., 2021, 2023; Kim et al., 2010, 2016), emphasizing their plasticity. Hence, we can assume that such changes occur and affect caregiver-infant interaction

across all levels of communication. Differences between infants' rapidly changing and immature neural systems and caregivers' mature neural systems can result in different changes caused by the interaction. Taken together, this approach explains how, in addition to caregivers' sensitivity and adaptability in forming a contingent dyadic communicative dance, infants must be considered not only as responders but also as proactive communicative partners from the very first days of postnatal life.

CONCLUSION

In this article, we proposed a developmental model of primal communication at the commencement of life that features an elaborated three-level communication system operating in infancy and after, and we explored its importance in developing secure affiliative bonds that serve as a template for future social interactions. Our model suggests a developing system that relies at first on autonomic responses and a narrow behavioral repertoire that evolves in the first year of life, setting the stage for the symbolic communication capacity that emerges later. This extended framework accounts for a broad scope of social interaction, hosting both the conscious information bits of what can be seen or sensed and the deeply rooted ones that activate strong footprints in humans' evolving social communication and attachment networks.

LOOKING AHEAD

We call for more extensive research addressing involuntary behaviors and autonomic responses not only as an outcome but as conveying, at times, a communicative value, mainly when symbolic output has not yet evolved and when it is no longer fully accessible due to degenerative processes (e.g., those related to aging, illness, or sensory disorders). This work can enrich theory-based research on the effects of dyadic interaction and on detecting risk for atypical development.

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CONFLICT OF INTEREST STATEMENT

We have no known conflict of interest to disclose.

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REFERENCES

Adolphs, R. (2001). The neurobiology of social cognition. *Current Opinion in Neurobiology*, *11*(2), 231–239. https://doi.org/10.1016/s0959-4388(00)00202-6

Ahmad, S., Wu, Y., Wu, Z., Thung, K. H., Liu, S., Lin, W., Li, G., Wang, L., & Yap, P. T. (2023). Multifaceted atlases of the human brain in its infancy. *Nature Methods*, *20*(1), 55–64. https://doi.org/10.1038/s41592-022-01703-z

Atzil, S., Gao, W., Fradkin, I., & Barrett, L. F. (2018). Growing a social brain. *Nature Human Behaviour*, *2*(9), 624–636. https://doi.org/10.1038/s41562-018-0384-6

Beebe, B., & Lachmann, F. M. (2015). The contribution of mother-infant mutual influence to the origins of self-and object representations. In N. J. Skolnick & S. C. Warshaw (Eds.), *Relational perspectives in psychoanalysis* (pp. 83–117). Routledge.

Blair, C., & Ursache, A. (2011). A bidirectional model of executive functions and self-regulation. In K. D. Vohs & R. F. Baumeister (Eds.), *Handbook of self-regulation: Research, theory, and applications* (2nd ed., pp. 300–320). The Guilford Press.

Camoirano, A. (2017). Mentalizing makes parenting work: A review about parental reflective functioning and clinical interventions to improve it. *Frontiers in Psychology*, *8*, 14. https://doi.org/10.3389/fpsyg.2017.00014

Carpendale, J. I., & Carpendale, A. B. (2010). The development of pointing: From personal directedness to interpersonal direction. *Human Development*, *53*(3), 110–126. https://doi.org/10.1159/000315168

Carpenter, M., Nagell, K., & Tomasello, M. (1998). Social cognition, joint attention, and communicative competence from 9 to 15 months of age. *Monographs of the Society for Research in Child Development*, *63*(4), i–174. https://www.ncbi.nlm.nih.gov/pubmed/9835078

Cherry, C. (1966). *On human communication*. The MIT Press.

Ciaunica, A., Constant, A., Preissl, H., & Fotopoulou, K. (2021). The first prior: From co-embodiment to co-homeostasis in early life. *Consciousness and Cognition*, *91*, 103117. https://doi.org/10.1016/j.concog.2021.103117

Cohen, L., & Billard, A. (2018). Social babbling: The emergence of symbolic gestures and words. *Neural Networks*, *106*(October), 194–204. https://doi.org/10.1016/j.neunet.2018.06.016

De Schuymer, L., De Groote, I., Desoete, A., & Roeyers, H. (2012). Gaze aversion during social interaction in preterm infants: A function of attention skills? *Infant Behavior and Development*, *35*(1), 129–139. https://doi.org/10.1016/j.infbeh.2011.08.002

Diaz-Rojas, F., Matsunaga, M., Tanaka, Y., Kikusui, T., Mogi, K., Nagasawa, M., Asano, K., Abe, N., & Myowa, M. (2021). Development of the paternal brain in expectant fathers during early pregnancy. *NeuroImage*, *225*, 117527. https://doi.org/10.1016/j.neuroimage.2020.117527

Diaz-Rojas, F., Matsunaga, M., Tanaka, Y., Kikusui, T., Mogi, K., Nagasawa, M., Asano, K., Abe, N., & Myowa, M. (2023). Development of the paternal brain in humans throughout pregnancy. *Journal of Cognitive Neuroscience*, *35*(3), 396–420. https://doi.org/10.1162/jocn_a_01953

Engel, M. L., & Gunnar, M. R. (2020). The development of stress reactivity and regulation during human development. *International Review of Neurobiology*, *150*, 41–76. https://doi.org/10.1016/bs.irn.2019.11.003

Farroni, T., Massaccesi, S., Pividori, D., & Johnson, M. H. (2010). Gaze following in newborns. *Infancy*, *5*(1), 39–60. https://doi.org/10.1207/s15327078in0501_2

Fawcett, C., Wesevich, V., & Gredeback, G. (2016). Pupillary contagion in infancy: Evidence for spontaneous transfer of arousal. *Psychological Science*, *27*(7), 997–1003. https://doi.org/10.1177/0956797616643924

Feldman, R. (2012). Parent–infant synchrony: A biobehavioral model of mutual influences in the formation of affiliative bonds. *Monographs of the Society for Research in Child*

Development, *77*(2), 42–51. https://doi.org/10.1111/j.1540-5834.2011.00660.x

Feldman, R., Magori-Cohen, R., Galili, G., Singer, M., & Louzoun, Y. (2011). Mother and infant coordinate heart rhythms through episodes of interaction synchrony. *Infant Behavior and Development*, *34*(4), 569–577. https://doi.org/10.1016/j.infbeh.2011.06.008

Field, T. M. (1981). Infant gaze aversion and heart rate during face-to-face interactions. *Infant Behavior and Development*, *4*(March), 307–315. https://doi.org/10.1016/S0163-6383(81)80032-X

Filippetti, M. L. (2021). Being in tune with your body: The emergence of interoceptive processing through caregiver–infant feeding interactions. *Child Development Perspectives*, *15*(3), 182–188. https://doi.org/10.1111/cdep.12420

Fotopoulou, A., & Tsakiris, M. (2017). Mentalizing homeostasis: The social origins of, Mentalizing homeostasis: The social origins of interoceptive inference interoceptive inference. *Neuropsychoanalysis*, *19*(1), 3–28. https://doi.org/10.1080/15294145.2017.1294031

Ger, E., Altınok, N., Liszkowski, U., & Küntay, A. C. (2018). Development of infant pointing from 10 to 12 months: The role of relevant caregiver responsiveness. *Infancy*, *23*(5), 708–729. https://doi.org/10.1111/infa.12239

Gergely, G., & Watson, J. S. (1996). The social biofeedback model of parental affect-mirroring. *The International Journal of Psychoanalysis*, *77*(6), 1181.

Geva, R., Dital, A., Ramon, D., Yarmolovsky, J., Gidron, M., & Kuint, J. (2017). Brainstem as a developmental gateway to social attention. *Journal of Child Psychology and Psychiatry, and Allied Disciplines*, *58*(12), 1351–1359. https://doi.org/10.1111/jcpp.12746

Geva, R., & Feldman, R. (2008). A neurobiological model for the effects of early brainstem functioning on the development of behavior and emotion regulation in infants: Implications for prenatal and perinatal risk. *Journal of Child Psychology and Psychiatry*, *49*(10), 1031–1041. https://doi.org/10.1111/j.1469-7610.2008.01918.x

Geva, R., & Orr, E. (2016). Talk the walk: Does socio-cognitive resource reallocation facilitate the development of walking? *PLoS One*, *11*(6), e0156351. https://doi.org/10.1371/journal.pone.0156351

Goldinger, S. D., & Papesh, M. H. (2012). Pupil dilation reflects the creation and retrieval of memories. *Current Directions in Psychological Science*, *21*(2), 90–95. https://doi.org/10.1177/0963721412436811

Goldstein, M. H., & Schwade, J. A. (2008). Social feedback to infants' babbling facilitates rapid phonological learning. *Psychological Science*, *19*(5), 515–523. https://doi.org/10.1111/j.1467-9280.2008.02117.x

Goldstein, M. H., Schwade, J. A., & Bornstein, M. H. (2009). The value of vocalizing: Five-month-old infants associate their own noncry vocalizations with responses from caregivers. *Child Development*, *80*(3), 636–644. https://doi.org/10.1111/j.1467-8624.2009.01287.x

Gomez, J. C. (2007). Pointing behaviors in apes and human infants: A balanced interpretation. *Child Development*, *78*(3), 729–734. https://doi.org/10.1111/j.1467-8624.2007.01027.x

Gredeback, G., & Daum, M. M. (2015). The microstructure of action perception in infancy: Decomposing the temporal structure of social information processing. *Child Development Perspectives*, *9*(2), 79–83. https://doi.org/10.1111/cdep.12109

Grienenberger, J. F., Kelly, K., & Slade, A. (2005). Maternal reflective functioning, mother-infant affective communication, and infant attachment: Exploring the link between mental states and observed caregiving behavior in the intergenerational transmission of attachment. *Attachment & Human Development*, *7*(3), 299–311. https://doi.org/10.1080/14616730500245963

Gros-Louis, J., West, M. J., Goldstein, M. H., & King, A. P. (2016). Mothers provide differential feedback to infants' prelinguistic sounds. *International Journal of Behavioral Development*, *30*(6), 509–516. https://doi.org/10.1177/0165025406071914

Grossmann, T. (2013). Mapping prefrontal cortex functions in human infancy. *Infancy*, *18*(3), 303–324. https://doi.org/10.1111/infa.12016

Grossmann, T., Parise, E., & Friederici, A. D. (2010). The detection of communicative signals directed at the self in infant prefrontal cortex. *Frontiers in Human Neuroscience*, *4*, 201. https://doi.org/10.3389/fnhum.2010.00201

Hodges, E. A., Propper, C. B., Estrem, H., & Schultz, M. B. (2020). Feeding during infancy: Interpersonal behavior, physiology, and obesity risk. *Child Development Perspectives*, *14*(3), 185–191. https://doi.org/10.1111/cdep.12376

Hoehl, S., Fairhurst, M., & Schirmer, A. (2021). Interactional synchrony: Signals, mechanisms and benefits. *Social Cognitive and Affective Neuroscience*, *16*(1–2), 5–18. https://doi.org/10.1093/scan/nsaa024

Hym, C., Forma, V., Anderson, D. I., Provasi, J., Granjon, L., Huet, V., Carpe, E., Teulier, C., Durand, K., Schaal, B., & Barbu-Roth, M. (2021). Newborn crawling and rooting in response to maternal breast odor. *Developmental Science*, *24*(3), e13061. https://doi.org/10.1111/desc.13061

Jackson, I., & Sirois, S. (2009). Infant cognition: Going full factorial with pupil dilation. *Developmental Science*, *12*(4), 670–679. https://doi.org/10.1111/j.1467-7687.2008.00805.x

James, W. (1890). Discrimination and comparison. In W. James (Ed.), *The principles of psychology* (Vol. *1*, pp. 483–549). Henry Holt and Co. https://doi.org/10.1037/10538-013

Kagan, J., & Herschkowitz, N. (2006). *A young mind in a growing brain*. Psychology Press.

Kim, P., Leckman, J. F., Mayes, L. C., Feldman, R., Wang, X., & Swain, J. E. (2010). The plasticity of human maternal brain: Longitudinal changes in brain anatomy during the early postpartum period. *Behavioral Neuroscience*, *124*(5), 695–700. https://doi.org/10.1037/a0020884

Kim, P., Strathearn, L., & Swain, J. E. (2016). The maternal brain and its plasticity in humans. *Hormones and Behavior*, *77*(January), 113–123. https://doi.org/10.1016/j.yhbeh.2015.08.001

Kolb, B., Mychasiuk, R., Muhammad, A., Li, Y., Frost, D. O., & Gibb, R. (2012). Experience and the developing prefrontal cortex. *Proceedings of the National Academy of Sciences of the United States of America*, *109*, 17186–17193. https://doi.org/10.1073/pnas.1121251109

Kret, M. E. (2015). Emotional expressions beyond facial muscle actions. A call for studying autonomic signals and their impact on social perception. *Frontiers in Psychology*, *6*, 711. https://doi.org/10.3389/fpsyg.2015.00711

Lavelli, M., & Fogel, A. (2005). Developmental changes in the relationship between the infant's attention and emotion during early face-to-face communication: The 2-month transition. *Developmental Psychobiology*, *41*(1), 265–280. https://doi.org/10.1037/0012-1649.41.1.265

Leclere, C., Viaux, S., Avril, M., Achard, C., Chetouani, M., Missonnier, S., & Cohen, D. (2014). Why synchrony matters during mother-child interactions: A systematic review. *PLoS One*, *9*(12), e113571. https://doi.org/10.1371/journal.pone.0113571

Lemaitre, H., Auge, P., Saitovitch, A., Vincon-Leite, A., Tacchella, J. M., Fillon, L., Calmon, R., Dangouloff-Ros, V., Levy, R., Grevent, D., Brunelle, F., Boddaert, N., & Zilbovicius, M. (2021). Rest functional brain maturation during the first year of life. *Cerebral Cortex*, *31*(3), 1776–1785. https://doi.org/10.1093/cercor/bhaa325

Leppanen, J. M., & Nelson, C. A. (2009). Tuning the developing brain to social signals of emotions. *Nature Reviews Neuroscience*, *10*(1), 37–47. https://doi.org/10.1038/nrn2554

Liszkowski, U. (2013). Using theory of mind. *Child Development Perspectives*, *7*(2), 104–109. https://doi.org/10.1111/cdep.12025

Ludwig, R. J., & Welch, M. G. (2020). How babies learn: The autonomic socioemotional reflex. *Early Human Development*, *151*(December), 105183. https://doi.org/10.1016/j.earlhumdev.2020.105183

Ludwig, R. J., & Welch, M. G. (2022). Wired to connect: The autonomic socioemotional reflex arc. *Frontiers in Psychology*, *13*, 841207. https://doi.org/10.3389/fpsyg.2022.841207

Mahler, M. S. (1958). Autism and symbiosis, two extreme disturbances of identity. *The International Journal of Psychoanalysis*, *39*(2–4), 77–83. https://www.ncbi.nlm.nih.gov/pubmed/13574940

Malachowski, L. G., & Needham, A. W. (2023). Infants exploring objects: A cascades perspective. *Advances in Child Development and Behavior*, *64*, 39–68. https://doi.org/10.1016/bs.acdb.2022.11.001

Marchak, F. M. (2013). Detecting false intent using eye blink measures. *Frontiers in Psychology*, *4*, 736. https://doi.org/10.3389/fpsyg.2013.00736

Mulkey, S. B., Govindan, R. B., Hitchings, L., Al-Shargabi, T., Herrera, N., Swisher, C. B., Eze, A., Jr., Russo, S., Schlatterer, S. D., Jacobs, M. B., McCarter, R., Kline, A., Maxwell, G. L., Baker, R., & du Plessis, A. J. (2021). Autonomic nervous system maturation in the premature extrauterine milieu. *Pediatric Research*, *89*(4), 863–868. https://doi.org/10.1038/s41390-020-0952-0

Mundy, P. (2018). A review of joint attention and social-cognitive brain systems in typical development and autism spectrum disorder. *European Journal of Neuroscience*, *47*(6), 497–514. https://doi.org/10.1111/ejn.13720

Mundy, P., & Newell, L. (2007). Attention, joint attention, and social cognition. *Current Directions in Psychological Science*, *16*(5), 269–274. https://doi.org/10.1111/j.1467-8721.2007.00518.x

Orr, E., & Geva, R. (2015). Symbolic play and language development. *Infant Behavior and Development*, *38*(February), 147–161. https://doi.org/10.1016/j.infbeh.2015.01.002

Petersen, S. E., & Posner, M. I. (2012). The attention system of the human brain: 20 years after. *Annual Review of Neuroscience*, *35*, 73–89. https://doi.org/10.1146/annurev-neuro-062111-150525

Porges, S. W., & Furman, S. A. (2011). The early development of the autonomic nervous system provides a neural platform for social behavior: A polyvagal perspective. *Infant and Child Development*, *20*(1), 106–118. https://doi.org/10.1002/icd.688

Prochazkova, E., & Kret, M. E. (2017). Connecting minds and sharing emotions through mimicry: A neurocognitive model of emotional contagion. *Neuroscience and Biobehavioral Reviews*, *80*(September), 99–114. https://doi.org/10.1016/j.neubiorev.2017.05.013

Prochazkova, E., Prochazkova, L., Giffin, M. R., Scholte, H. S., De Dreu, C. K. W., & Kret, M. E. (2018). Pupil mimicry promotes trust through the theory-of-mind network. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(31), E7265–E7274. https://doi.org/10.1073/pnas.1803916115

Ramenzoni, V. C., & Liszkowski, U. (2016). The social reach: 8-month-olds reach for unobtainable objects in the presence of another person. *Psychological Science*, *27*(9), 1278–1285. https://doi.org/10.1177/0956797616659938

Rodriguez, C. (2022). The construction of executive function in early development: The pragmatics of action and gestures. *Human Development*, *66*(4–5), 239–259. https://doi.org/10.1159/000526340

Rothbart, M. K., Sheese, B. E., & Posner, M. I. (2007). Executive attention and fffortful control: Linking temperament, brain networks, and genes. *Child Development Perspectives*, *1*(1), 2–7. https://doi.org/10.1111/j.1750-8606.2007.00002.x

Rothbart, M. K., Sheese, B. E., Rueda, M. R., & Posner, M. I. (2011). Developing mechanisms of self-regulation in early life. *Emotion Review*, *3*(2), 207–213. https://doi.org/10.1177/1754073910387943

Shai, D., & Belsky, J. (2011). When words just won't do: Introducing parental embodied mentalizing. *Child Development Perspectives*, *5*(3), 173–180. https://doi.org/10.1111/j.1750-8606.2011.00181.x

Shinya, Y., Kawai, M., Niwa, F., & Myowa-Yamakoshi, M. (2016). Associations between respiratory arrhythmia and fundamental frequency of spontaneous crying in preterm and term infants at term-equivalent age. *Developmental Psychobiology*, *58*(6), 724–733. https://doi.org/10.1002/dev.21412

Tamietto, M., & de Gelder, B. (2010). Neural bases of the non-conscious perception of emotional signals. *Nature Reviews Neuroscience*, *11*(10), 697–709. https://doi.org/10.1038/nrn2889

Tanaka, Y., Kanakogi, Y., & Myowa, M. (2021). Social touch in mother-infant interaction affects infants' subsequent social engagement and object exploration. *Humanities and Social Sciences Communications*, *8*(1), 1–11. https://doi.org/10.1057/s41599-020-00642-4

Tomasello, M., Carpenter, M., & Liszkowski, U. (2007). A new look at infant pointing. *Child Development*, *78*(3), 705–722. https://doi.org/10.1111/j.1467-8624.2007.01025.x

Trevarthen, C., & Aitken, K. J. (2001). Infant intersubjectivity: Research, theory, and clinical applications. *Journal of Child Psychology and Psychiatry*, *42*(1), 3–48. https://www.ncbi.nlm.nih.gov/pubmed/11205623

Tronick, E. Z. (2018). Emotions and emotional communication in infants. *American Psychologist*, *44*(2), 112–119. https://doi.org/10.1037/0003-066X.44.2.112

Wass, S. V., Smith, C. G., Clackson, K., Gibb, C., Eitzenberger, J., & Mirza, F. U. (2019). Parents mimic and influence their infant's autonomic state through dynamic affective state matching. *Current Biology*, *29*(14), 2415–2422.e4. https://doi.org/10.1016/j.cub.2019.06.016

Welch, M. G., & Ludwig, R. J. (2017). Calming cycle theory and the co-regulation of oxytocin. *Psychodyn Psychiatry*, *45*(4), 519–540. https://doi.org/10.1521/pdps.2017.45.4.519

Winnicott, D. W. (1960). The theory of the parent–infant relationship. *The International Journal of Psychoanalysis*, *41*, 585–595. https://www.ncbi.nlm.nih.gov/pubmed/13785877

Woodhouse, S. S., Scott, J. R., Hepworth, A. D., & Cassidy, J. (2020). Secure base provision: A new approach to examining links between maternal caregiving and infant attachment. *Child Development*, *91*(1), e249–e265. https://doi.org/10.1111/cdev.13224

Yamamoto, H., Sato, A., & Itakura, S. (2019). Transition from crawling to walking changes gaze communication space in everyday infant–parent interaction. *Frontiers in Psychology*, *10*, 2987. https://doi.org/10.3389/fpsyg.2019.02987

Yarmolovsky, J., & Geva, R. (2023). Follow the leader: Parent-and child-led synchrony in competitive and cooperative play. *Journal of Nonverbal Behavior*, 1–17. https://doi.org/10.1007/s10919-023-00445-6

Zeng, G., Maylott, S. E., Leung, T. S., Messinger, D. S., Wang, J., & Simpson, E. A. (2022). Infant temperamental fear, pupil dilation, and gaze aversion from smiling strangers. *Developmental Psychobiology*, *64*(7), e22324. https://doi.org/10.1002/dev.22324

Zeskind, P. S. (2013). Infant crying and the synchrony of arousal. In E. Altenmüller, S. Schmidt, & E. Zimmermann (Eds.), *Evolution of emotional communication: From sounds in nonhuman mammals to speech and music in man* (pp. 155–172). Oxford University Press.

Zivan, M., Morag, I., Yarmolovsky, J., & Geva, R. (2021). Hyperreactivity to salience limits social interaction among infants born pre-term and infant siblings of children with ASD. *Frontiers in Psychiatry*, *12*, 646838. https://doi.org/10.3389/fpsyt.2021.646838

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