# INVESTIGATING DYADIC SOCIAL COORDINATION AND INFANT ATTENTION IN TYPICAL AND ATYPICAL DEVELOPMENT

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For human infants, social interactions with adults can provide various opportunities for learning and communicative development. To take advantage of such opportunities, infants must learn to control and allocate attention effectively to others' social cues, using attentional skills that have been described under the broader term of "social attention". While prior theories suggested that infants possess certain social attentional skills from very early in development, recent work in ecologically-relevant settings indicates that specific aspects of reciprocal social coordination between infants and their caregivers may significantly influence the development of social attention abilities, as well as the development of attentional control broadly. In my thesis, I expand upon more recent findings of infant attention in everyday social contexts, by exploring how differences in the *timing* (contingency) and *content* (spatial/semantic alignment) of adults' social responses to infants' behaviors relate to individual differences both in infants' immediate visual attention patterns in social settings, and in later neurodevelopmental outcomes. Within Study 1, I demonstrate that 5-month-olds whose caregivers exhibit high ratios of attentional *redirection* (attempts to shift focus) in response to infants' behaviors during naturalistic play show more distractibility in response to caregivers' broader behaviors, as well as less visual engagement with caregivers' held objects compared to infants whose caregivers exhibit high contingent *sensitivity* (joint responsiveness). Study 2 takes an experimental approach, showing that both the rate and sensitivity/redirectiveness of experimenters' controlled responses to 6-7-month-olds' behaviors during a social interaction interact to influence infants' immediate attention to experimenters' object-related actions. Additionally, Study 2 explores connections between contingency, content, and behavioral arousal, illustrating that experimenters' rate of responding predicts infant visual indices of arousal on a subsequent vigilance task. Finally, Study 3 explores infant social attention patterns and caregiver responding among 6-10-month-olds at high risk for autism (ASD), suggesting that higher sensitive responding to vocalizations at 6-10 months predicts enhanced learning outcomes at 36 months among children who receive an ASD diagnosis. Together, these studies contribute to our understanding of dyadic influences on early attention development, and help to clarify the relative influences of temporal and spatial/semantic coordination on infant social attention and learning.

BIOGRAPHICAL SKETCH

Gina Marie Mason completed her undergraduate degree *magna cum laude* at the University of Arizona in Tucson, where she double majored in molecular-cellular biology and psychology with honors and minored in Spanish language and literature. It was at the University of Arizona where Gina initially discovered her love of research, as she worked under the mentorship of Drs. Lynn Nadel and Jamie Edgin in the Down Syndrome Research Group (DSRG). While working with the DSRG, Gina completed an honors thesis investigating relations between polymorphic variation in non-trisomy 21 genes, and differences in attention and inhibitory control in children and young adults with Down syndrome.

After taking a year to work further with the DSRG as a laboratory manager, Gina moved to Ithaca to begin her graduate studies with Drs. Michael H. Goldstein and Jennifer Schwade in the Eleanor J. Gibson laboratory of Developmental Psychology. At Cornell, she has studied the dyadic and neuropsychological underpinnings of visual attention organization in human infants, using both observational and experimental approaches. Gina has also continued her work in atypical development, collaborating with researchers in the British Autism Study of Infant Siblings (BASIS) network to assess dyadic coordination and infant social attention among infants at high risk for autism. Following completion of her Ph.D., Gina with join the research group of Dr. Rebecca Spencer at the University of Massachusetts-Amherst, where she will study the role of sleep in social-emotional memory consolidation in preschool age children.

In her limited spare time, Gina enjoys volunteering with local science communication organizations (locallysourcedscience.org), as well as music, the outdoors, and spending time with her friends and family.

Dedicated to Dave and Elizabeth, and to everyone else who has supported me along this journey.

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Notably, I would like to thank all of the infants, children and families who participated in my studies, both in Ithaca (studies 1 and 2) and as part of the BASIS project (study 3). Without your commitment, our research would not have been possible. Finally, I would like to thank my own friends and family, for continually encouraging me to follow and achieve my aspirations.

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# INTRODUCTION

For humans and non-human animals alike, our external world provides many sources of sensory input that can be used to inform future behavior. In describing the processes by which our brains and bodies select which information is prioritized and integrated into neural representation and action, many have used the term *attention* (Aston-Jones, Rajkowski, & Cohen, 1999; Itti & Koch, 2001; James, 1896), and learning to attend adaptively to the most relevant information at any given moment is regarded as a significant aspect of early development (Bakeman & Adamson, 1984; Colombo, 2002; Deák, Triesch, Krasno, de Barbaro, & Robledo, 2013; Mundy et al., 2007). Reflecting on attention in the case of the human infant, how might infants learn to regulate their attention adaptively? And, what *is* adaptive attention in the context of human infants' early milieu?

Many diverse perspectives have been put forth to explore the above questions, though one frequent theme among them is that humans' high degree of sociality means that adaptive early attention must include the ability to effectively attend to others' social and communicative signals (Deák et al., 2013). Indeed, both historical and recent studies have attempted to explain the concept of human "social attention" and its early requisites (Goren, Sarty, & Wu, 1975; Kagan & Lewis, 1965; Morton & Johnson, 1991; Salley & Colombo, 2016; Wilkinson, Paikan, Gredebäck, Rea, & Metta, 2014), and neurodevelopmental conditions such as autism (ASD) and attention-deficit hyperactivity disorder (ADHD) are commonly characterized in terms of impairments in attention that have implications for social interaction and communication (Dawson et al., 2004; Guillon, Hadjikhani, Baduel, & Rogé, 2014; Uekermann et al., 2010). Considering that part of our background as a species includes a greatly extended period of parental care and interactions with multiple others who can provide us with various learning and cooperative opportunities (Balshine, 2012), it makes sense that researchers and clinicians would place an emphasis on early social attention skills as an area of importance when contemplating infant attention development. So, how are early attention skills constructed within early social contexts?

In the present thesis, I aim to explore the concept of social attention, and how specific aspects of infants' interactions with caregivers and adults may mechanistically relate to differences in early attention in everyday environments. In order to provide the necessary framework for the studies that follow, I will first describe how prior theorists have studied and conceptualized of infant social attention, and additionally discuss current viewpoints on dyadic (caregiver-infant) influences on infant attention and social development. I will then introduce each of my chapters, beginning with observational accounts of infant attention in naturalistic social settings, and ending with application of the ideas gleaned from observational and experimental data to inform studies of interaction among parent-infant dyads at high risk for neurodevelopmental conditions.

**Exploring "Social Attention": Do the eyes have it?**

Without question, most classic and current work on infant attention development, whether pertinent to social attention or more general attention processes, has focused on some form of visual orientation on the part of the infant to stimuli of interest. While not always the case (Kagan & Lewis, 1965; Richards & Casey, 1991; Robertson, Watamura, & Wilbourn, 2012), often this focus has meant that infant attention is measured via infants' overt visual fixations (eyegaze), with the more mainstream perspective being that infant looking represents information processing and/or preference for a stimulus of interest (e.g. Colombo & Mitchell, 1988; Cuevas & Bell, 2014; Rhodes, Geddes, Jeffery, Dziurawiec, & Clark, 2002).

With regard to “social attention”, many classic studies measured social attention in terms of infant looking preferences and physiological reactions to stimuli that were regarded to be inherently “social”, such as drawings, pictures, or representations of human faces (Goren et al., 1975; Kagan & Lewis, 1965; Morton & Johnson, 1991). Kagan & Lewis (1965) were two of the first individuals to document an early face preference in infants, noting that looking preferences for (i.e., longer looking toward) faces at 6 months were accompanied by other indices of attention such as heart rate decelerations, reduced motor activity, and an increase in vocalizing for particular faces. This initial report was followed by other studies that attempted to delineate whether infants’ looking preferences for faces were present at birth, as such a preference was thought to potentially indicate an early evolutionary adaptation for discriminating socially-relevant stimuli (Goren et al., 1975; Johnson, Dziurawiec, Ellis, & Morton, 1991). Though it was shown through these studies that newborns did often track face-like stimuli with greater visual responsiveness than stimuli of presumably equal complexity (i.e., “scrambled” face-pattern images), the interpretation of such findings as a specifically social evolutionary adaptation have been consequently debated (Simion, Valenza, Cassia, Turati, & Umiltà, 2002; Turati, 2004; Wilkinson et al., 2014). Despite these uncertainties, other studies have gone on to expand notions of infants’ early face preferences to include early looking preferences for eyes specifically (Batki, Baron-Cohen, Wheelwright, Connellan, & Ahluwalia, 2000), and clinical researchers have subsequently employed measures of face processing and gaze detection in efforts to assess early behavioral and neural signatures of neurodevelopmental conditions such as autism (Elsabbagh et al., 2012; Jones & Klin, 2013)

**New horizons in social attention: Infant attention in natural social environments**

While early face preferences in infants may or may not represent a specialized evolutionary adaptation for encouraging early looking to social stimuli, a broader question more recently posed regarding infant social attention is how social attention manifests more naturally in infants' everyday looking environments. Specifically, many of the studies discussed above tested infants in experimental settings in which the social stimuli being presented were part of a limited array of possible areas to which infants could attend (e.g., see methods in Goren et al., 1975). However, infants' typical environments arguably contain various uncontrolled sources of multimodal stimulation and distraction that may compete for infants' attention (Clerkin, Hart, Rehg, Yu, & Smith, 2017); and, when allowed to roam freely, infants' own physical and perceptual capabilities may also help to determine when and to what their attention is allocated (Smith, Jayaraman, Clerkin, & Yu, 2018). Considering these issues, more recent work has made a number of advancements in quantifying and describing infant looking within more free-form social contexts, including their own home environments (Clerkin et al., 2017; Deák, Krasno, Triesch, Lewis, & Sepeta, 2014; Fausey, Jayaraman, & Smith, 2016) as well as in laboratory paradigms in which infants are given greater degrees of freedom in terms of moving and interacting with tangible objects and adult social partners (Goldstein, Schwade, Briesch, & Syal, 2010; Kretch, Franchak, & Adolph, 2014; Miller, Ables, King, & West, 2009; Yu & Smith, 2012, 2017). Such studies have demonstrated that social attention can be (and often is) a fully embodied process, in which the timing of infants' attention is just as relevant as what the infant chooses to fixate on.

As a case in point, many of the studies above have shown that while infants may show a looking preference for faces in laboratory environments, faces are present in less than half (specifically, in approximately 25%, or 15 minutes of every hour) of young infants' everyday visual experiences according to studies using head cameras to capture infants' home-based moment-by-moment views (Fausey et al., 2016; Jayaraman, Fausey, & Smith, 2015). Furthermore, the presence of faces declines steadily with age, as infants also become more proficient at coordinating their eyes and hands to act on the surrounding environment (de Barbaro, Johnson, & Deák, 2013; Fausey et al., 2016). While the presence of others' faces in 25% of young infants' visual scenes may still be considered fairly high given that such faces are often close and visually prominent during the moments in which they are present (Jayaraman et al. 2015), such data reinforce the notion that faces are not the *only* stimuli that infants are interested in visually attending to, despite the nearly constant presence of caregivers in natural settings. Within play contexts especially, infants from at least 3-11 months of age do not show a visual looking preference for their caregivers' faces, but rather attend to objects that their caregivers are holding or touching over other areas of focus (Deák et al., 2014). From these discoveries and other insights (i.e. Johnson, 2011; Butterworth & Cochran, 1980; Deák et al., 2013), researchers have generally acknowledged that at least in typical environments, innate face preferences are not enough to learn to adaptively attend to others' more subtle social cues.

Instead, given infants' preferences for dynamically moving and close-range objects including those manipulated by their caregivers, more recent theories have converged on the notion that social attention skills can perhaps be developed over time through the bidirectional coordination of caregivers' and infants' manual actions and eyegaze (Deák et al., 2014; Yu & Smith, 2017). More specifically, during the few moments in which infants do attend to caregivers' faces in naturalistic environments, these moments appear particularly timely, as caregivers at these moments are most likely than expected (Deák et al., 2014) to be looking either at the infant, or at the objects that they themselves are holding. Through these instances in which infants attend to adults' objects and subsequently attend to their faces, it is thought that infants may build a predictive expectation that adults' faces and eyes are often directed to visually "interesting" or infant-preferred objects and areas (Deák et al., 2014), thus providing infants an incentive for developing further gaze-following and dynamic attention-sharing skills. The above argument will be revisited continually throughout my thesis, though it is important also to elucidate here because it sets the premise for why observations of infant attention in naturalistic contexts are so crucial: such observations allow us to build theories and models that are reflected in real-world data, which may in turn allow us to come closer to true mechanisms of change in infant social attention development.

**Caregiver-infant coordination and individual differences**

With the studies described above, we have set the stage for an argument that infant social attention should be considered beyond looking preferences in highly controlled paradigms, and that interactions with adults may provide valuable input to help scaffold infants' development of further social and adaptive attentional skills. This argument thus begs the question: are certain styles or types of interaction more facilitative than others for fostering infant social attention organization? Additionally, might individual differences in infants' social attention reflect differences in the social contexts provided by their adult interaction partners? And, do caregivers also change their behavior based on the feedback they receive from their infants?

For each of the above questions, we can provide a tentative affirmation, as many studies have suggested that the presence of certain forms of temporal and spatial/semantic coordination between infants and caregivers help to promote attention and learning outcomes that are considered beneficial (Goldstein et al., 2010; Miller & Gros-Louis, 2013; Miller & Gros-Louis, 2017; Yu & Smith, 2016). Throughout my chapters, I will be continually returning to the concept of *contingency,* which indicates that social partners are coordinating the timing of their responses reliably based on one another's behavior. Alongside the timing of social partners' responses however, there is also the matter of the *content* of their responses, and whether social partners' response content is congruent with, or *sensitive* to, what the other is focused on (McGillion et al., 2013). To be clear, various lines of research have described the concept of caregiver sensitivity using definitions that have encompassed a wide range of elements, including the broader emotional and affective characteristics of the caregiver (e.g., "warmth", "positivity", "authenticity"; Biringen et al., 2014; Wan et al., 2017) as well as the degree of spatial, temporal and semantic congruence present within her or his responses. When employing such definitions, researchers have commonly measured sensitivity using 'macro' level techniques, in which they use global scale-type ratings to describe caregivers' sensitivity as perceived broadly across an entire adult-infant interaction (e.g. Pederson et al., 1990; Biringen et al., 2014; Wan et al., 2017; Bornstein & Manian, 2013). While these macro-level approaches may provide us with a general sense of the overall quality of social exchanges between adult-infant dyads, such approaches can also be problematic in that they often do not give us a clear picture of the moment-by-moment dynamics of adults' responses, particularly given the many characteristics (emotional, affective, temporal, etc.) that raters are taking into account when assigning sensitive ratings on a macro-scale. Within the studies presented below, we adopt a more 'micro'-level approach to sensitivity (e.g. Baumwell, Tamis-Lemonda & Bornstein 1997; Goldstein et al. 2010), in which contingent sensitive responses are identified moment-by-moment during adult-infant interactions and are defined simply as any response to an infant's behavior that is aligned spatially, and/or provides more information (either verbally, behaviorally, or multimodally) about the object or area that the infant is visually attending to at the moment of response. Such an approach allows us to more precisely define and focus our investigations on a subset of components present within adult-infant exchanges, and to determine more closely whether these specific components (in comparison to potentially more ambiguous or subjective constructs) relate to differences in infant attention and learning as they unfold during the interaction.

Considering caregiver-infant interaction from a microanalytic perspective, developmentalists often regard contingent sensitive responding to be most favorable in terms of early attention organization and learning (Baumwell, Tamis-LeMonda, & Bornstein, 1997; Goldstein et al., 2010; Miller & Gros-Louis, 2017). However, that is not to say that contingent sensitivity is the most optimal in every context, and it is indeed possible that in some environments, higher rates of other types of responses often regarded as discordant or incongruent (such as *redirectiveness*, in which social partners attempt to shift one another's foci) may assist in training children to be attentive to dynamically changing or unstable settings. Additionally, infants' own behaviors certainly also influence the types of responses that adults provide (Albert, Schwade, & Goldstein, 2017), and recent work elucidating the reciprocity of influence between members of the caregiver-infant dyad have described this reciprocity as a "social feedback loop" in the realm of speech development (Goldstein & Schwade, 2009; Warlaumont, Richards, Gilkerson, & Oller, 2014). Thus, while I use the terms 'sensitivity' and 'redirectiveness' to describe adult social partners' behaviors towards infants in the studies below, I do not intend to necessarily evoke qualitative judgments of the positivity or negativity of these behaviors for infants' overall development, as it is likely that the relative impact of these response types on child outcomes also depends on various characteristics of the infant and of the broader environment (e.g. Shimpi & Huttenlocher 2007). Rather, I endeavor to more extensively elucidate the components of the previously proposed social feedback loop within the context of social attention, both by observing the structures present in naturally-occurring interactions between infants and caregivers, and by experimentally manipulating certain elements within these structures as infants interact with unfamiliar social partners. Though beyond the scope of the studies described here, future work in our laboratory also aims to quantify step-by-step relations between adults' and infants' actions during dyadic exchanges (Figure I1), as doing so may allow us to predict how changes in the strength of the relations between different behaviors (either within the same dyad over time, or between different dyads at similar developmental timepoints) might correspond to differences in immediate and later social learning.

## The Present Work: Investigating Dyadic Social Coordination and Infant Attention in Typical and Atypical Development

My thesis consists of three parts. In Study 1, I investigate how natural variation in caregivers' contingent sensitivity and redirectiveness covaries with differences in infant social attention patterns recently considered significant for cognitive development in real-world social settings. Next, I present Study 2, which takes and experimental and neurobiologically-informed approach to determining whether novel adults' controlled social responding may produce real-time changes in attention and arousal that carry over into a consequent perceptual-attentional task. Finally, I also assess parent-infant interaction and longitudinal cognitive outcomes among infants at high genetic risk for autism, both to help elucidate how risk status may influence early social attention and interaction between infants and their parents, and also to explore whether certain microbehavioral aspects of parent responding may be associated with enhanced outcomes among children with and without ASD. From this work, I hope that I may contribute additional insights into mechanisms underlying infant social attention development, as well as into how infants' own behaviors and abilities may help to constrain and shape their social learning environments.

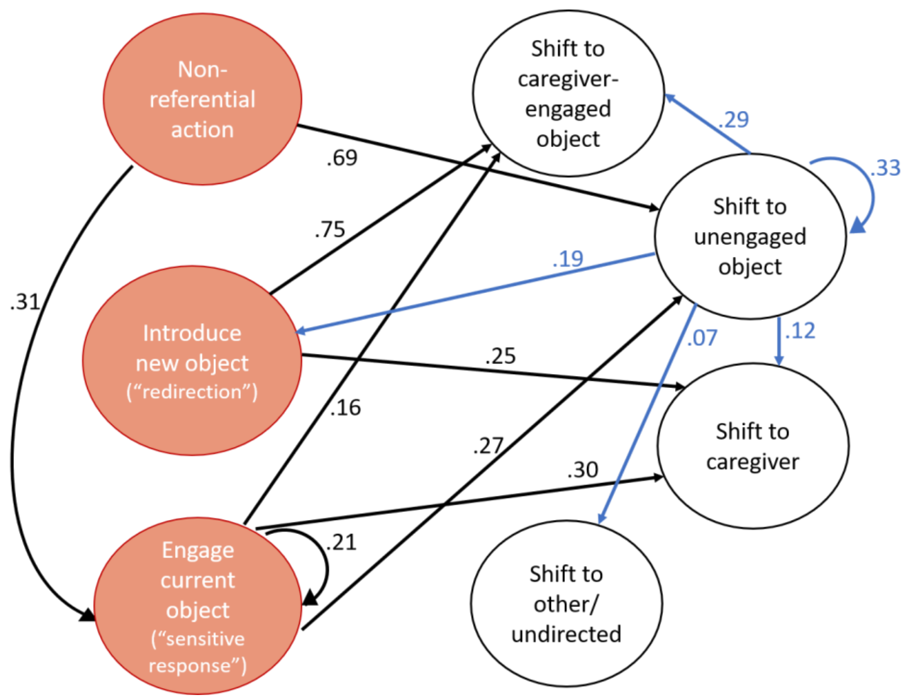


Figure I1. Example finite-state diagram illustrating transitional probabilities between caregiver and infant behaviors during a dyadic interaction. Pink-filled circles represent caregiver actions, while white-filled circles represent infant actions. Additionally, black arrows depict transitional probabilities following a caregiver action, while blue arrows illustrate transitional probabilities following a specific infant action ("Shift to unengaged object"). For simplicity, transitional probabilities following other possible infant actions (i.e., shifts to caregiver-engaged objects, shifts to the caregiver, and shifts to other/undirected areas) are omitted.

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# CHAPTER 1

## THE ROLE OF DYADIC COORDINATION IN ORGANIZING VISUAL ATTENTION IN 5-MONTH-OLD INFANTS

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Abstract

In human infants, the ability to share attention with others is facilitated by increases in attentional selectivity and focus. Differences in early attention have been associated with socio-cognitive outcomes including language, yet the social mechanisms of attention organization in early infancy have only recently been considered. Here, we examined how social coordination between 5-month-old infants and caregivers relate to differences in infant attention, including looking preferences, span, and reactivity to caregivers' social cues. Using a naturalistic play paradigm, we found that 5-month-olds who received a high ratio of *sensitive* (jointly focused) contingent responses showed strong preferences for objects with which their caregivers were manually engaged. In contrast, infants whose caregivers exhibited high ratios of *redirection* (attempts to shift focus) showed no preferences for caregivers' held objects. Such differences have implications for recent models of cognitive development, which rely on early looking preferences for adults' manually-engaged objects as a pathway towards joint attention and word learning. Further, sensitivity and redirectiveness predicted infant attention even in reaction to caregiver responses that were *non-referential* (neither sensitive nor redirective). In response to non-referentials, infants of highly sensitive caregivers oriented less frequently than infants of highly redirective caregivers, who showed increased distractibility. Our results suggest that specific dyadic exchanges predict infant attention differences toward broader social cues, which may have consequences for social-cognitive outcomes.

The role of dyadic coordination in organizing visual attention in 5-month-old infants

Across early development, human infants are immersed in an environment in which various opportunities for growth and learning are embedded in the structure of social behavior (Goldstein, Waterfall, et al., 2010; Goldstein & Schwade, 2009; Yu & Smith, 2012). As infants explore their surroundings, caregivers and other adults provide diverse forms of social feedback to their behaviors (Crown, Feldstein, Jasnow, Beebe, & Jaffe, 2002; de Barbaro, Johnson, & Deák, 2013; Gros-Louis, West, Goldstein, & King, 2006). Such feedback can provide infants with vital information about the social and physical environments, as well as the grammatical and phonological structure of their surrounding language (Goldstein & Schwade, 2008; Goldstein, Schwade, Briesch, & Syal, 2010; Wu, Gopnik, Richardson, & Kirkham, 2011).

In order to gain access to the information available from social interactions, infants must develop the ability to control their attention, so that they can flexibly maintain focus on the environmental and social cues relevant to their current needs and goals. Additionally, infants must select and distinguish which cues are in fact relevant in the midst of potential distractions. Such skills converge over time and experience to allow infants to engage in *attention sharing* with adults and other social partners (Deák, Triesch, Krasno, de Barbaro, & Robledo, 2013). Along with gaze following, attention sharing is considered a critical precursor to more triadic and deliberate joint attention, in which children and adults reciprocally direct and share attention on a third point of reference (Carpenter, Nagell, Tomasello, Butterworth, & Moore, 1998). Accordingly, early attention sharing skills among infants and caregivers have been related to immediate learning and long-term communicative outcomes (Mundy et al., 2007; Yu & Smith, 2012), whereas difficulties in early attentional control, selection and sharing have been implicated in later neurodevelopmental diagnoses (Dawson et al., 2004; Elsabbagh et al., 2013). While such findings emphasize the importance of understanding the processes underlying early attentional abilities, there are still many unknowns regarding how infants learn to control, direct and share attention across early experience, including which factors are most influential in determining individual differences.

To explain how infants learn to control and share attention, previous research has focused on identifying intrinsic properties of human adults that may explain emerging attentional abilities as well as variation across individuals. For instance, some findings have suggested that from birth, infants are biased to visually attend to socially-relevant stimuli, including others' faces and eyes (Morton & Johnson, 1991). Subsequent psychologists have interpreted these biases as reflecting a specialized and inherent attunement to social cues regardless of postnatal dyadic experience (Batki, Baron-Cohen, Wheelwright, Connellan, & Ahluwalia, 2000), proposing that individual differences in attention sharing arise via deficits in these specialized systems (Senju, Yaguchi, Tojo, & Hasegawa, 2003). However, more recent work in naturalistic environments suggests that skills including shared attention and gaze following arise gradually and are incrementally refined and improved, presumably through experience and learning (e.g. Corkum & Moore, 1998; Deák et al., 2014; Yu & Smith, 2016; also see Deák et al., 2013 for review). Infants' apparent interest in faces and eyes has also been shown to vary with development when assessed in more ecologically-relevant settings, as new motor skills and postures afford different vantage points from which to explore other objects and areas of potential appeal (Deák et al., 2014; Fausey, Jayaraman, & Smith, 2016; Kretch, Franchak, & Adolph, 2014). Such findings indicate that the development of attention sharing may be more dependent on experience than previously thought, and that early visual biases towards others' faces are not sufficient to explain developmental change (see Karmiloff-Smith et al., 1998 for a framework by which to consider the relative interactions between early domain-relevant predispositions and experience in the development of complex behavior).

Based on recent findings, current theories on the emergence of attention sharing and gaze following have proposed that these skills may be shaped by infants' early interactions with their caregivers. Specifically, infants may learn to share and follow gaze through dyadic experiences that allow them to associate their caregivers' direction of gaze with predictive value (Gottlieb, Oudeyer, Lopes, & Baranes, 2013; Oudeyer & Smith, 2016), as well as with locations of objects and sights that infants find interesting and rewarding (Moore & Corkum, 1994; Triesch, Teuscher, Deák, & Carlson, 2006). Such theories require caregivers' social cues to have a strong *social signal-to-noise* ratio (SSNR), meaning that the number of caregiver visual cues that create predictable events around an infant's focus of attention should be greater than the number of cues that are non-predictive or irrelevant to infants' attention. To explore whether such predictive structure is present in caregivers' cues, subsequent studies have characterized infants' and caregivers' visual behavior during home-based and semi-naturalistic dyadic interactions (Deák et al., 2014; Yu & Smith, 2013). Both paradigms suggest that infants across the first year often prefer attending to objects that caregivers are manually manipulating during caregiver-object play (though see Jayaraman, Fausey, & Smith, 2015 for a broader analysis of infant looking across various dyadic activities), and that caregivers often also attend to these objects. Subsequently, during the rare moments in which infants do attend to caregivers' faces, caregivers are often shifting gaze to the objects that infants strongly prefer, namely the objects they are touching or holding (Deák et al. 2014). Such dyadic patterns imply that it is possible for infants to learn to associate caregivers' eye gaze with rewarding sights, as caregivers' gaze cues often align with the objects that their infants prefer. Furthermore, infants' apparent looking preferences for handled objects may be a crucial requisite for learning social cues, given that caregivers' eye gaze and manual focus tend to overlap reliably (Yu & Smith 2013).

Building on the presence of reliable structure in caregivers' responses to infant looking, new work has begun to explore how caregivers' social cues may consequently influence the development of broader abilities supporting joint attention, such as attentional maintenance and word learning.  For instance, when parents share visual attention with objects that their 12-month-olds focus on, infants extend their gaze duration on those objects even after their parents stop attending to them (Yu and Smith, 2016). Additionally, when parents verbally label objects that their toddlers are holding and visually isolating, toddlers are more likely to learn these object labels and subsequently attend to these objects when prompted by a new adult (Yu & Smith, 2012). These results indicate that parents' social cues may help to strengthen older infants' and toddlers' own attentional maintenance and cue following, which may have implications for future joint attention outcomes.

Given the importance of caregivers' social feedback for the development of skills supporting joint attention, does variability in caregivers' social coordination with their infants help to predict or explain individual differences in such abilities? Social coordination is often multimodal, incorporating verbal and visual behavior in organizing the timing and content of parental feedback.  The timing of such coordination is critical.  Many studies have found that caregivers' verbal responses and other behaviors are more likely to influence infant attention and learning when they are coordinated reliably and promptly with (i.e., are *contingent* on) infants' behaviors. The efficacy of caregiver contingency has been demonstrated especially in studies of word-object learning (Goldstein, Schwade, et al., 2010) and in studies of general attentional organization (Dunham, Dunham, Hurshman, & Alexander, 1989).

Within the repertoire of contingent responses, however, the physical and semantic alignment of caregivers' contingent behaviors with infants' focus has also been associated with differences in learning and attention (McGillion et al., 2013; Landry, Smith, & Swank, 2006). Developmental psychologists have used the term *sensitivity* to describe a vast array of both stable and developmentally variable caregiver behaviors that may indicate attunement to infants' attentional or emotional state (e.g. Ainsworth, 1979; Bornstein, Tamis-LeMonda, Hahn, & Haynes, 2008; Mesman, 2010; Bigelow et al., 2010). On a microstructural level, sensitivity more specifically denotes moment-by-moment instances in which caregivers' contingent responses follow and are congruent with infants' visual focus of attention. When defined in this framework, contingent verbal sensitivity during infancy positively predicts early vocabulary and language comprehension (Baumwell, Tamis-LeMonda, & Bornstein, 1997; Tomasello & Farrar, 1986), and more recent experimental work has suggested increased social attentional engagement and improved social learning among infants interacting with verbally sensitive adults (Miller & Gros-Louis, 2016).

In contrast to sensitive responses, another type of contingent behavior typically considered divergent from sensitivity is *redirectiveness*. Redirectiveness describes caregiver behaviors that attempt to shift or distract infants from their current object of focus, implying a lack of congruency between the caregiver's focus and that of the infant (e.g. Baumwell et al., 1997; Tomasello & Farrar, 1986). At the microbehavioral level, redirectiveness among social partners and caregivers has been linked to increased moment-by-moment distractibility in older infants, as well as lower vocabulary size at later ages (Miller, Ables, King, & West, 2009; Miller

& Gros-Louis, 2013; Tomasello & Farrar, 1986, though see Shimpi & Huttenlocher, 2007). Taken together, the findings on contingency, sensitivity, and redirectiveness support the notion that both the form and timing of caregivers' interactions with infants may influence dyadic coordination, and that contingent sensitivity and redirectiveness in particular may be critical when considering early social influences on infant attention organization.

In the present study, we investigated how differences in caregivers' relative levels of contingent sensitivity and redirectiveness might relate to individual differences in infants' visual attention in social contexts. In particular, we explored how different response structures relate to: 1) Differences in infants' looking preferences to caregiver-handled objects; 2) Infants' general distractibility; and, 3) Infants' moment-by-moment reactions to caregivers' contingent responses.

***Do differences in caregiver sensitivity/redirectiveness predict differences in infants' social looking preferences*?** Regarding looking preferences, recent joint attention models support a strong role for early looking preferences toward adults' manually-engaged objects as a pathway towards joint attention (Deák et al. 2014, 2013; Yu & Smith, 2013). Such models beg the question: do differences in caregiver sensitivity and redirectiveness promote or discourage infants' visual preference for caregiver-handled objects? We predicted that if caregivers' actions are more sensitive on average, then infants should show strong preferences for their caregivers' objects, as they are more likely to have learned that their caregivers are often engaged with objects that they themselves find visually rewarding. In contrast, if caregivers' actions are more redirective on average (i.e., incongruent with infants' object focus), then infants may learn that their caregivers are not likely to be engaged with the objects that they themselves are demonstrating an interest in. Subsequently, we predicted that infants of highly redirective caregivers should not show any clear preference for looking at caregiver-manipulated vs. unengaged (static) objects.

***Do differences in caregiver sensitivity/redirectiveness predict differences in infants' general attention span?*** Another early factor proposed by Deák et al. (2013) to be important for attention sharing is the degree to which infants *exploit* or maintain attention on their current task or object of gaze, vs. *exploring* and seeking out other potentially rewarding stimuli (Aston-Jones & Cohen, 2005). Previous experimental findings have related redirective social interactions to infant distractibility (Miller et al. 2009), while other findings have related parents' visual sensitivity with increases in older infants' attention durations (Yu & Smith, 2016). Accordingly, we expected high levels of caregiver sensitivity to encourage increased *exploitation* and attentional maintenance on the part of infants. In contrast, we expected high levels of caregiver redirectiveness to cause increased arousal on the part of infants, in turn corresponding to higher rates of gaze shifting (*exploration*) as well as a greater tendency to seek out new salient objects when shifting gaze.

***Do differences in caregiver sensitivity/redirectiveness predict differences in infants' attentional reactivity toward social cues specifically?*** One final skill important for attention sharing and overall communicative development is the ability to differentiate which social behaviors are relevant to attend and respond to, and which are not (Kuchirko, Tafuro, & Tamis Lemonda, 2017). Considering how caregiver sensitivity and redirectiveness might facilitate or hinder infants' ability to distinguish relevant social cues, we expected high caregiver sensitivity to correspond with more refined and appropriate social attentional attunement on the part of infants (Kuchirko et al. 2017), and high redirectiveness to correspond with less selectivity and increased distractibility in response to caregivers' behaviors. To examine the effects of caregiver sensitivity and redirectiveness on infants' attention toward broader social cues, we assessed infants' reactions to their caregivers' contingent responses overall as well as specifically to responses that were *non-referential*, that is, not related to any object or area of focus in the infant's immediate environment. Because non-referentials are not intended to direct infants' attention to a particular location, we predicted that infants' reactions to non-referentials may illuminate potential attentional biases and habits learned from the overall SSNR (predictable structure) of their caregivers' behaviors. Specifically, we hypothesized that infants of relatively sensitive caregivers should not be distracted by non-referentials, as they may have learned that their caregivers' behaviors are generally congruent with infants' attentional focus. In contrast, infants of relatively redirective caregivers may be more distracted by non-referentials, as they have associated their caregivers' behavior with a change in focus. As redirections often elicit attention to new objects, we also hypothesized that infants of highly redirective caregivers would perhaps shift intuitively toward objects in response to non-referentials also, whereas infants of highly sensitive caregivers would not have an obligatory pattern of focus when reacting to non-referentials.

To explore our primary questions, we used *micro*-level methods (for a discussion of macro- vs. micro- approaches, see Hsu & Fogel, 2003) to characterize 5-month-olds' visual attention patterns during dyadic social interactions. We focused on 5-month-olds because social learning and attention preferences are already robust at this age (Goldstein, Schwade, & Bornstein, 2009; Deák et al., 2014), and individual differences in attentional patterns (i.e., habituation) are detectable by this age as well (e.g. Colombo, Mitchell, Coldren, & Freeseman, 1991). However, the effects of caregiver sensitivity and redirectiveness on attention in infants younger than 6 months are currently less known. The present study aimed to predict how early differences in social feedback (particularly, high SSNRs of caregiver sensitivity or redirectiveness) might influence infant gaze behaviors that potentially contribute to later attention and learning differences. Overall, we hypothesized that high caregiver sensitivity should predict more typical infant gaze preferences and social attunement as found in prior observational work, while high caregiver redirectiveness should correspond to less social attunement, higher distractibility, and lack of a clear preference for attending to objects that caregivers are manipulating.

## Method

### *Participants*

To analyze caregivers' social behavior, data were derived from a sample of convenience consisting of 67 caregivers and their five-month-old infants (30 female, 37 male; mean age 5 months, 10 days (range 147-183 days)). These dyads were part of a larger ongoing longitudinal study assessing relations between infant vocal learning at five months and later language ability, and were recruited via birth announcements, flyers and community outreach events in Ithaca, New York. Of the 67 caregivers evaluated, 65 completed our demographic survey. Caregivers' mean ages were 32.6 years (mother; range 23-47 years) and 34.1 years (partner/spouse; range 24-61 years). Approximately 86.4% of respondents were White, Non-Hispanic; the remaining 13.6% identified as African-American (1.7%), Chinese (3.4%), Latino/South American (3.4%), Puerto Rican (1.7%), Pakistani (1.7%), or Biracial (1.7%). Additionally, all who responded had completed at least some college at the time of the study, with the majority (80.3%) having obtained a Bachelor's degree or higher.

For infant attention analyses, we selected infants whose caregivers were classified as exhibiting the highest SSNRs of either sensitivity (*HS* group) or redirectiveness (*HR* group) in the overall sample (Figure 1.2c; for full description of selection criteria, see Coding and Dyad Selection below). The final sample of infants whose caregivers matched this criterion was 17 (7 *HS*, 10 *HR*). Infants in each group had no known health issues or developmental diagnoses at the time of the study, and the groups did not significantly differ in age (mean *HS* = 159 days; mean *HR* = 161 days), sex distribution (in *HS*= 3 females of 7, in *HR*= 5 females of 10), number of siblings (mean *HS* < 1 sibling, mean *HR* < 1 sibling), parents' ethnicity (# White non-Hispanic in *HS*= 6 of 7, in *HR*= 8 of 10) or parents' education level (# parents with a Bachelor's Degree or higher in *HS* = 5 of 7, in *HR* = 8 of 10) (*p*s > .36 for all).

*Materials*

For the free-play activity, infants and their caregivers were recorded in a 12 x 18 ft. playroom using 3 wall-mounted Sony® DCR-TRV900 camcorders, which were positioned to capture multiple viewing angles. A toy box containing a standard set of age-appropriate toys was made available for infants' and caregivers' use, along with a circular play mat placed in the center of the room. The presence of the toys and the spaciousness of the play area were designed to encourage free range of movement and interaction between the infant and caregiver in an unstructured and semi-naturalistic context. Additionally, caregivers wore a wireless microphone (Telex FMR 1000) to capture their verbal prompts and responses, while infants wore a pair of customized overalls outfitted with a concealed wireless microphone and transmitter (Telex FMR 500) to record their vocalizations during the play session.

*Procedure*

The present study was conducted according to guidelines laid down in the Declaration of Helsinki, with written informed consent obtained from a parent or guardian for each child before any assessment or data collection. All procedures involving human subjects in this study were approved by the Institutional Review Board at Cornell University. After obtaining informed consent, a trained researcher video-recorded infants and their caregivers as they engaged in a short set of tasks designed to assess both social and nonsocial abilities underlying vocal learning at age 5 months. Dyads participated in a 15-minute unstructured play session in our laboratory playroom. For this task, caregivers were instructed to play with their infant as they would at home with the toys provided, and were given no additional prompts. However, caregivers and infants were allowed to take breaks and resume play if the infant became fussy throughout the interaction. Additionally, the first 5 minutes of the interaction served as a warm-up period for the caregivers and infants, to allow them to become accustomed to the room, toys and cameras. Thus, all subsequent analyses were restricted to the last ten minutes. The order in which infants and caregivers completed the play session relative to other activities within the broader study was randomized and counterbalanced, and infants received a t-shirt, bib, or toy prize for participation.

*Coding and Dyad Selection*

Following video recording, one trained coder blind to the current study questions reviewed the free play sessions and identified all infant vocalizations and sustained fixations (i.e., looks lasting longer than 0.5 seconds; this criterion is in accord with “meaningful fixation” thresholds used in other infant literature (e.g., Fernald, Zangl, Portillo, & Marchman, 2008; de

Barbaro et al. 2011), while also incorporating considerations of adults' typical fixation durations and the minimum event durations needed to notice an infant behavior (Wass & Smith, 2014)). The coder then identified caregiver responses that occurred *contingently* on (i.e., within 2 seconds of; Gros-Louis, West, Goldstein, & King, 2006; McGillion et al., 2013) these infant behaviors. Caregivers' contingent responses were labeled using one of the following categories: *Sensitive response* (a response congruent in space and time with the infant's own focus of attention following a long look or vocalization by the infant); *redirective response* (an active attempt to direct the infant's attention away from his or her current focus in response to a long look or vocalization); and, *non-referentials* (imitations, narrative responses unrelated to infants' focus, non-sequiturs, or affirmations; laughs, exclamations, and inspirations were also included within this category). More detailed descriptions and examples of each response classification are shown in Table 1.1[1].

After caregivers' responses had been quantified, researchers calculated the proportions of sensitive and redirective behaviors displayed by each caregiver relative to their total responses (Figure 1.2a-c). The distributions of these proportions allowed us to identify caregivers who exhibited the highest social signal-to-noise ratios of either sensitivity or redirectiveness in the sample. *Highest Sensitive/Low Redirective* (*HS*) caregivers fell into the top 25% of sensitivity and the bottom 50% of redirectiveness. *Highest Redirective/Low Sensitive* (*HR*) caregivers fell into the top 25% of redirectiveness and the bottom 50% of sensitivity. The final sample consisted of 17 dyads (*HS*=7, *HR*=10).

[1] Additional details on the coding schemes, including full coding manuals, are available on Open Science Framework (OSF) at https://osf.io/qfgez/

Once infants had been targeted for analysis, the first author (who was blind to infants' caregiver group assignments) coded both long and short bouts of infant visual attention behaviors, using procedures modified from Deák et al. (2014) and Miller, Ables, King, & West,

TABLE 1.1
Description of Caregiver Contingent Response Types and Examples

| ***Response Type*** | ***Description*** | ***Verbal Examples*** | ***Nonverbal/Multimodal Examples*** |
|---|---|---|---|
| *Sensitive* responses | Response congruent in space and time with the infant's own focus of attention | Infant looks and/or babbles at toy, then caregiver labels same toy within 2sec; infant babbles or focuses on caregiver, then caregiver says "hi"/acknowledges look verbally within 2 sec | Infant looks and/or babbles at toy, then caregiver picks up same toy (or picks up toy and labels) with 2 sec; infant looks/babbles at caregiver, and caregiver plays dyadic game ("peekaboo" with hands covering face, etc.) within 2 sec |
| | | *Special Sensitive Cases (Verbal and Nonverbal/Multimodal)*:<br><br>***Social referencing***: infant looks at toy, then looks at caregiver; response is sensitive if caregiver engages with the same toy that the infant had looked at directly prior<br><br>***Undirected looking***: caregiver's response is ***sensitive*** if (s)he attempts to engage infant with a toy or herself when infant is looking undirected | |
| *Redirective* responses | Attempt to direct the infant's attention away from his or her current focus | Infant looks and/or babbles at toy, but caregiver says "look at me!", "look at this other toy!", etc. Infant looks and/or babbles at caregiver, and caregiver verbally instructs infant to look at a toy that infant had not just been engaged with. | Infant looks and/or babbles at toy, but caregiver picks up a different toy in response. Infant looks/babbles at caregiver, and caregiver directs to an object that the infant had *not* been looking at directly prior. |
| *Non-referential (other)* responses | Statements or actions not related directly to the infant's current focus of attention | Conversational placeholders (e.g. gasps, aspirations, laughs); narrating the state of the infant but not what (s)he is focused on (e.g., "good job!" after an infant action; "look at you go!" when infant is moving, etc.); non-sequiturs (statements not related to anything in the immediate area or anything specific the baby is doing, e.g. "what's for dinner tonight?"); vocal imitations of infant babbles | Physical imitations of infant actions (for instance, mom crawls next to infant as infant is crawling; mom claps hands after infant claps hands; etc.) |

(2009). Coding was completed using ELAN video annotation software created by the Language Archive at the Max Planck Institute for Psycholinguistics in Nijmegen, the Netherlands (https://tla.mpi.nl/tools/tla-tools/elan/; Sloetjes & Wittenburg, 2008). Infant visual fixations and shifts of attention were indexed frame-by-frame at 30 frames per second. Infants' focus of looking was classified under one of the following categories (Figure 1.1[1]): *objects* (during periods in which caregivers were manipulating objects, this category was sub-classified as *caregiver-engaged* or *static*, to capture moments in which infants were and were not attending to the caregivers' handled object), *caregiver* (including the caregiver's face, upper body and hands), *other/undirected areas* (this included the walls, ceiling and floor of the playroom, as well as the infant's own body and the caregiver's lower body), and *uncodable time,* which was excluded during analyses (this included moments in which infants' eyes or areas of focus were out-of-view of the current camera view, as well as instances in which infants' eyes were closed). In order to classify infants' object looking as *caregiver-engaged* or *static,* the first author additionally identified all instances in which caregivers touched, manipulated, or held objects during the interaction, regardless of the time window between such actions and infants' preceding actions. Infants were characterized as looking at *caregiver-engaged* objects during frames in which they were fixated on the object(s) that the caregiver was manipulating, while *static object* looking occurred during frames in which infants were fixated on a different object than the one that the caregiver was manipulating.

Additionally, when assessing infant gaze shifting during short (< 2 sec) caregiver handling bouts (which often occurred in rapid succession), we applied a 2-second contingency window to capture subsequent infant attention changes. As similar "bursts" of caregiver interactive behavior towards infants have been grouped using a 2-second criterion in previous

a. *Objects* (Caregiver-Engaged)

b. *Objects* (Static)

c. *Caregiver* (Including Hands)

d. *Other/Undirected*

*Figure 1.1*. Examples of free-play setup and infant looking. a) Illustrates looks to caregiver-engaged (held or manipulated) objects, while b) depicts infant looks to caregiver-unengaged ("static") objects. c) Shows infant looking towards the caregiver (including caregivers' hands), and d) illustrates looks to undirected or other areas, such as the infant's own body. More examples and information on the coding scheme are available on Open Science Framework at https://osf.io/qfgez/.

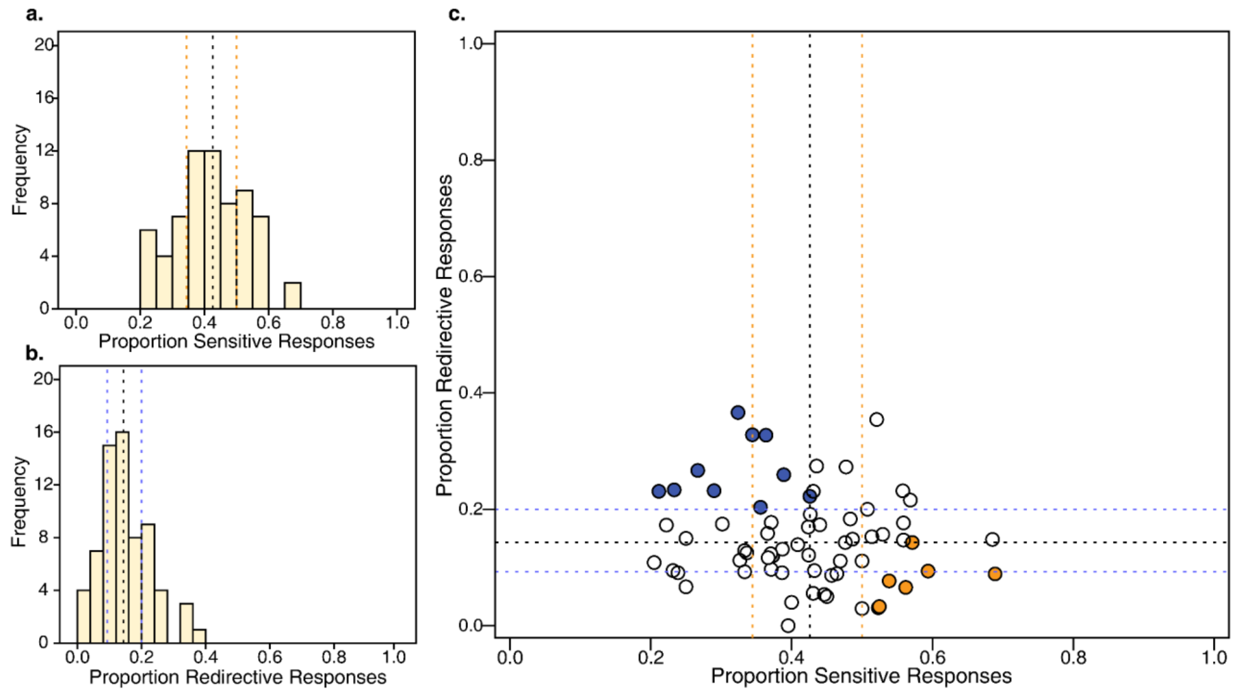


*Figure 1.2.* SSNRs of contingent sensitive and redirective responses exhibited by caregivers during free play (calculated as proportions of total contingent responses). (a) Displays the proportions of sensitive responses (relative to all contingent responses) in the sample, with dotted lines denoting distributional cutoffs at 25%, 50%, and 75% respectively. (b) Depicts the relative proportional distributions of redirective responses. In (c), the proportions of sensitive and redirective responses observed in each caregiver are displayed relative to one another. Caregivers whose infants were selected for attention analyses are highlighted in orange (*HS* caregivers) and blue (*HR* caregivers). Dotted orange lines represent the 25% (left) and 75% (right) cutoff values for sensitive responses, while dotted blue lines represent the 25% (bottom) and 75% (top) cutoff values for redirective responses. Dotted black lines represent the middle (50%) cutoff values for both distributions.

studies (see Kaye & Fogel, 1980), we considered object-handling bouts < 2 sec apart as continuous when examining whether infant attentional reorientations were occurring. Additionally, given that infants' average shift rate was approximately 1 shift every 2 seconds (mean(SD)=30.45(10.83) shifts/min; median=33.56 shifts/min), a 2-second contingency window seemed suitable to account for infant shifts that might occur in reaction to even the briefest of caregivers' object holds (see Keller, Lohaus, Völker, Cappenberg, & Chasiotis, 1999 for a discussion of the use of different contingency windows in examining dyadic coordination).

To assess reliability, two separate coders blind to both the infants' caregiver group assignment and to the overall hypotheses of the study recoded a randomly-selected subset of 25% of every video. One coder coded caregiver object handling and infant looking preferences, while the other coded infants' fine-grained attention shifts. Absolute intraclass correlation coefficients for infant attention variables ranged from strong to excellent (*single-measures*: .76 - .99; Supplemental Table S1.1), while the average absolute ICC value for caregiver object handling was .99, indicating nearly perfect agreement.

*Data Analyses*

Our primary analyses comprised 3 main objectives: 1) to characterize 5-month-olds' looking preferences during naturalistic social interactions, and to investigate whether caregivers' SSNRs of sensitivity and redirectiveness relate to differences in these preferences; 2) to compare 5-month-olds' attention dynamics (*exploitation* vs. *exploration*, measured by infants' gaze shift frequency) relative to their caregivers' SSNRs of sensitivity and redirectiveness; 3) and, to investigate whether caregivers' SSNRs of sensitivity and redirectiveness predict differences in infants' inclinations to shift visual attention specifically in reaction to caregivers' contingent responses. We also assessed whether increased sensitivity or redirectiveness covary with other aspects of caregiver behavior that might influence attention, such as overall activity levels and object handling.

We evaluated infants' looking preferences by comparing infants' proportional looking times at all possible regions of interest (see *Coding* above for description), while infant attention dynamics were assessed by obtaining indices of each infant's attention shifting during free play. To do this, we divided the total number of attention shifting events for each infant by the total minutes of codable time in their individual play sessions. We calculated separate indices of attention shifting during caregiver object handling vs. non-handling periods. Finally, we assessed the degree to which caregivers' contingent responses broadly elicited contingent infant attention shifts, by calculating the proportion of caregivers' behaviors that elicited a shift within 2 seconds (Gros-Louis et al., 2006).

We also assessed the specific impact of redirective and non-referential caregiver behavior on infant attention. Redirection success was measured by the proportions of caregivers' redirections in which the caregiver effectively shifted the infant's focus to a new object. Additionally, we calculated infants' average latencies to attend to the new object, as we viewed this as an additional measure of infants' attunement to caregivers' social cues. We also examined infant shifting in response to caregivers' non-referential responses, to identify attentional biases evidenced by shifting after receiving open-ended social feedback. After calculating each variable for individual dyads, values were averaged at the level of caregiver group (*HS* and *HR*), and groups were compared using ANOVA and t-test analyses.

## Results

### *Caregiver Response Structure*

**Broader caregiver sample**. Figure 1.2(a,b,c) details the overall proportions of contingent sensitive and redirective responses observed in our broader caregiver sample (n=67). Caregivers' SSNRs of sensitivity were approximately normally distributed (Figure 1.2a; mean SSNR = 41.9%, K-S test=0.06, $p > .20$), with values ranging from 20.5%-68.9% of all responses.

Compared to this range, caregivers exhibited relatively lower SSNRs of redirective responses, with values ranging from 0.0%-36.6% of all responses (Fig. 1.2b). Caregivers' redirective responses were also normally distributed (K-S test=0.09, $p > .20$).

Figure 1.2c plots each caregiver's individual proportions of sensitivity and redirectiveness relative to one another. There was no significant correlation between caregivers' relative levels of sensitive and redirective responding in the broader sample ($r(65)=-0.14$, $p=.25$). However, both sensitivity and redirectiveness were significantly negatively correlated with the proportions of non-referential responses (sensitivity & non-referentials: $r(65)=-0.78$, $p<.001$; redirectiveness & non-referentials: $r(65)=-0.51$, $p<.001$; (supplemental figure S1.1)). As all three response categories (sensitive, redirective, and non-referential) are mutually exclusive, the negative correlations between non-referential responses and the other response types are not surprising, particularly given the lack of correlation between levels of sensitive and redirective responding.

**Targeted caregiver groups**. As described in Methods, based on the proportions of sensitivity and redirectiveness observed in our sample, we selected infants of caregivers whose response proportions fell within the top 25% of sensitivity and bottom 50% of redirectiveness (*HS*), or within the top 25% of redirectiveness and bottom 50% of sensitivity (*HR*) (Figure 1.2c). While only a small sample of caregivers fell into these groups, these cutoffs allowed us to assess caregivers with the highest SSNRs of sensitivity and redirectiveness possible. At the group level, caregivers exhibited significantly disparate proportions of sensitivity and redirectiveness (Sensitivity: *HS* mean = 57.17%, *HR* mean = 32.04%, $t(15)=7.88$, $p < .01$; Redirectiveness: *HS* mean = 7.60%, *HR* mean = 26.69%, $t(15)= -7.92$, $p < .01$).

To evaluate whether *HS* and *HR* caregivers displayed differences in other relevant behaviors that might affect infant attention, such as general activity levels throughout the session, we also assessed caregivers' object handling and contingent responding. *HS* and *HR* caregivers did not significantly differ in their raw time spent engaged with objects (mean *HS*=166.05 sec, mean *HR*=211.70 sec, $t(15)=-0.96$, p= .35), or in their relative time engaging with objects during infants' codable looking periods (mean *HS*=27.92% of codable time, mean *HR*=36.55% of codable time; $t(15)=-1.06$, p = .31). Additionally, caregivers did not differ in their raw number of contingent responses (mean *HS*=77.29 responses, mean *HR*=64.00 responses, $t(7.03)=0.97$ p= .37) or in their rate of contingent responses across the session (assessed by dividing the raw number of contingent responses by total codable time: mean *HS*=8.78 responses/min, mean *HR*=8.08 responses/min, $t(15)=0.43$, p = .68). The contingent responses of HS and HR caregivers, when examined by modality (vocal, behavioral, combination of vocal and behavioral), also did not differ across groups (Supplemental Table S1.2). We next examined whether HS and HR caregivers differed in their speed of responding to infant behavior. Latencies of *HS* and *HR* caregivers' first contingent responses within infants' looks did not significantly differ (mean(SD) *HS*=1.80 (0.57) seconds, mean(SD) *HR*=1.46 (0.28) seconds, $t(8.05)=1.45$, p = .18).

Regarding codable time, all dyads had at least 6.5 minutes of codable time (minimum= 392.89 sec), with all but one dyad having greater than 7 minutes of codable time. These durations of codable time are in line with durations reported in previous studies assessing caregiver-infant interaction and attention (Deák et al., 2014; Miller et al., 2009;Wan et al., 2012; Hsu & Fogel, 2003). Between groups, *HS* and *HR* dyads did not differ significantly in their raw uncodable time when caregivers were engaged with objects (mean(SD) uncodable *HS*= 17.37

(21.41)sec, mean(SD) *HR*= 37.33 (28.06)sec, $t(15)=-1.58$, p=.14). Dyads also did not differ in their proportions of uncodable time relative to total engaged time (mean(SD) uncodable *HS*= 10.52% (7.19%) of total engaged time; mean(SD) *HR*= 16.85% (9.12%) of total engaged time; $t(15)= -1.53$, p=.15). However, when caregivers were not engaged, *HR* dyads had more uncodable time on average than *HS* dyads (raw uncodable *HS*= 35.98 (21.82)sec, raw uncodable *HR*= 72.95 (40.84)sec, $t(15)= -2.18$, p=.046; proportion uncodable *HS*= 8.68% (5.52%) of unengaged time, proportion uncodable *HR*= 19.61% (9.10%) of unengaged time, $t(15)=-2.82$, p=.013). To account for differences in codable time across dyads when assessing infant attention, we normalized infant looking times and overall attention shifting by calculating these variables as proportions and rates relative to each dyad's codable time (see *Data Analyses* above). Additionally, when assessing infant looking preferences during caregiver unengaged periods, we re-ran our analysis to include infants' uncodable time during these periods as a covariate. All significant findings remained; thus, the original analysis is reported below.

*Infant Attention*

**Do differences in caregivers' sensitivity/redirectiveness predict differences in infants' social looking preferences?** Figure 1.3(a,b) depicts the proportions of time that infants spent looking at different areas (looking categories; see Methods) while interacting with their caregivers. When caregivers were *not* engaged with objects (Fig. 1.3a), infants of both *HS* and *HR* caregivers spent more than half of their time attending to objects on average (mean *HS*= 71.09% of looking time; mean *HR*= 75.68% looking time). Their next highest looking category was undirected areas (mean *HS*= 15.20% of looking time; mean *HR* = 14.35% of total looking time), followed by caregiver areas (mean *HS*= 13.71% of looking time; mean *HR*= 9.96% of

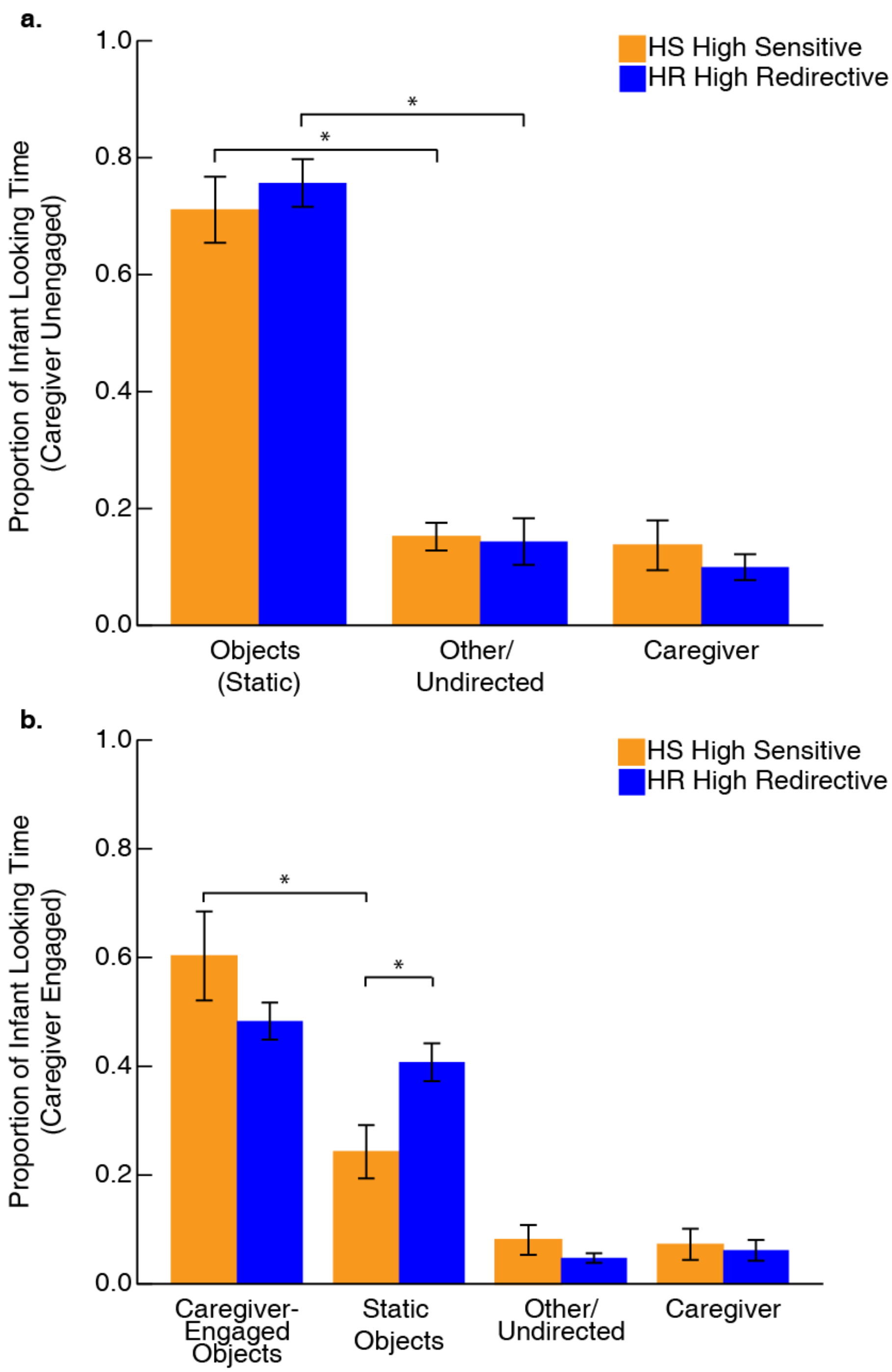


*Figure 1.3*. Infant looking times at relative areas of interest during social interactions with caregivers. Graphs show looking preferences of infants of *HS* and *HR* caregivers when: a) caregivers are not currently engaged with objects, and b) caregivers are manually engaged with at least one object. Orange bars denote mean proportions of looking time for infants of highly sensitive caregivers; blue bars denote mean proportions for infants of highly redirective caregivers. *p < .05

total looking time). To determine whether infants of *HS* and *HR* caregivers differed in their looking preferences, and whether their preferences for objects were significant, we ran a 2 (caregiver group) x 2 (looking category: objects vs. undirected areas) mixed ANOVA on infants' proportions of looking time (Fig. 1.3a). Because infants' looking categories are mutually exclusive and were assessed as relative proportions, we did not include the looking category that infants attended to the least (i.e., caregiver areas) in the analysis. This exclusion allows room for the summed proportions of the two looking categories included (objects and undirected areas) to vary such that the between-subjects term (caregiver group) can be assessed (for an example of a similar analysis strategy applied to proportions, see Deák et al., 2014). The 2x2 analysis revealed a significant main effect of looking category ($F(1,15) = 108.93$, $p < .001$), with no main effect of caregiver group, and no looking category x caregiver group interaction.

When caregivers *were* manually engaged with objects, infants again appeared to spend over half of their time attending to objects on average (Figure 1.3b). To determine whether infants of *HS* and *HR* caregivers significantly preferred looking at *caregiver-engaged* objects over static objects during these periods, we ran a 2 (caregiver group) x 2 (object type: caregiver-engaged vs. static) mixed ANOVA. There was a significant main effect of object type (caregiver-engaged vs. static: $F(1,15) = 10.995$, $p = .005$), with infants preferring to attend to caregiver-engaged objects over static objects. There was no significant main effect of caregiver group ($F(1,15)=0.998$, $p = .33$); however, there was a significant object type x group interaction ($F(1, 15)= 4.69$, $p = .047$). To explore this interaction further, we performed tests of simple main effects. These tests revealed that while infants of *HS* caregivers significantly preferred looking at caregiver-engaged over static objects ($F(1,6)=8.03$, $p = .030$), infants of *HR* caregivers showed no preference for looking at caregivers' held objects. Additionally, infants of *HR* caregivers spent a significantly greater proportion of time looking at static objects than infants of *HS* caregivers ($F(1,15)=8.01$, $p = .013$), though the two groups did not differ in their proportions of caregiver-engaged object looking.

**Do differences in caregiver sensitivity/redirectiveness predict differences in infants' general attention span?** To investigate how caregiver sensitivity and redirectiveness affect infants' attention span, we ran a mixed-model 2 (caregiver group) x 2 (caregiver handling state: engaged vs. unengaged with objects) mixed ANOVA on infants' average rate of gaze shifting. We found a marginal main effect of caregiver group, as infants of HS caregivers shifted gaze marginally less frequently than infants of HR caregivers $F(1,15) = 4.30$, $p = .056$) (Figure 1.4). There was a significant main effect of caregiver handling state, as infants of both *HS* and *HR* caregivers appeared to shift more frequently when their caregivers were *not* manually engaged with objects ($F(1,15) = 13.35$, $p = .002$). There was no significant interaction.

**Do differences in caregiver sensitivity/redirectiveness predict differences in infants' attentional reactivity toward social cues specifically?** We next examined how frequently infants shifted gaze specifically in reaction to (i.e., within 2 seconds of) their caregivers' contingent responses. First, to assess the direct effects of sensitive and redirective responses on infants' attentional reactivity, we compared across all dyads the proportions of responses that infants shifted to when the response was either sensitive or redirective[2]. Infants shifted gaze more frequently in reaction to redirective responses than to sensitive responses ($t(16) = -2.407$, $p = .029$; Figure 1.5). To examine *HS* and *HR* caregivers' redirection *success* independently, we

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[2] Because two of the seven *HS* infants received 2 or fewer redirective responses each across the entire social interaction (and more generally, because the number of sensitive and redirective responses from which to sample differed robustly between *HS* and *HR* groups), a mixed-model comparison was unfeasible for this analysis.

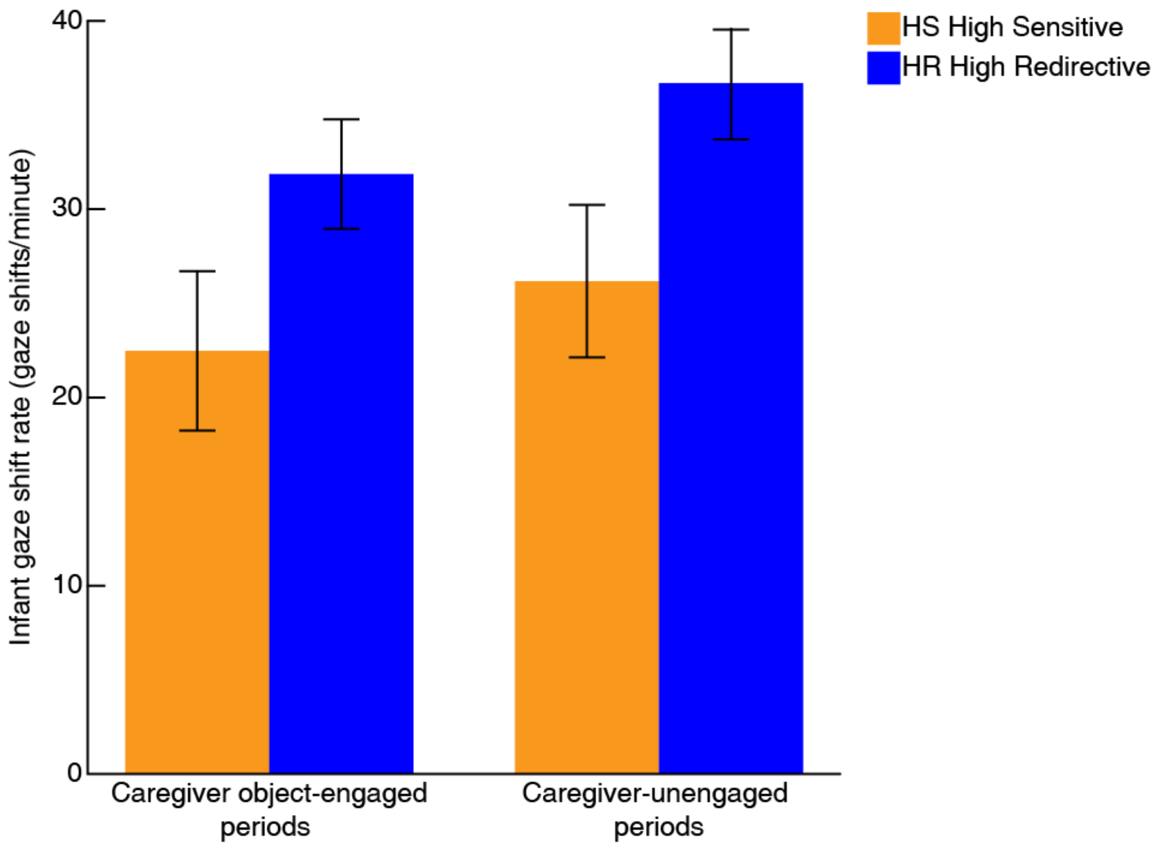


*Figure 1.4*. Overall gaze shifting rates for infants of *HS* and *HR* caregivers, during moments in which caregivers are engaged with objects and not engaged with objects. Orange bars denote mean rates for infants of highly sensitive caregivers; blue bars denote means for infants of highly redirective caregivers. There was a significant within-subjects main effect of caregivers' object handling on infants' shift rate, and a marginal between-subjects main effect (p=.056) of caregiver group.

next ran an exploratory analysis[3] quantifying the proportions of *HS* and *HR* caregivers' redirections that successfully caused infants to shift to the focus of the caregiver's attention. There were no significant between-groups differences in *HS* vs. *HR* caregivers' redirection success (*HS* success = 57.19% of all redirections, *HR* success = 49.80% of all redirections, $t(13) = .51$, $p = .62$). However, when exploring the specific latencies by which infants in both groups

[3] To prevent binary proportion (0% or 100%) values for this analysis, we excluded dyads whose caregivers had provided <2 target-specific redirections.

successfully followed caregivers' redirections, infants of highly sensitive caregivers more quickly followed their caregivers' redirective prompts than infants of *HR* caregivers (*HS* mean infant latency = .60 seconds, *HR* mean = 1.05 seconds, $t(13) = -3.27$, p = .006).

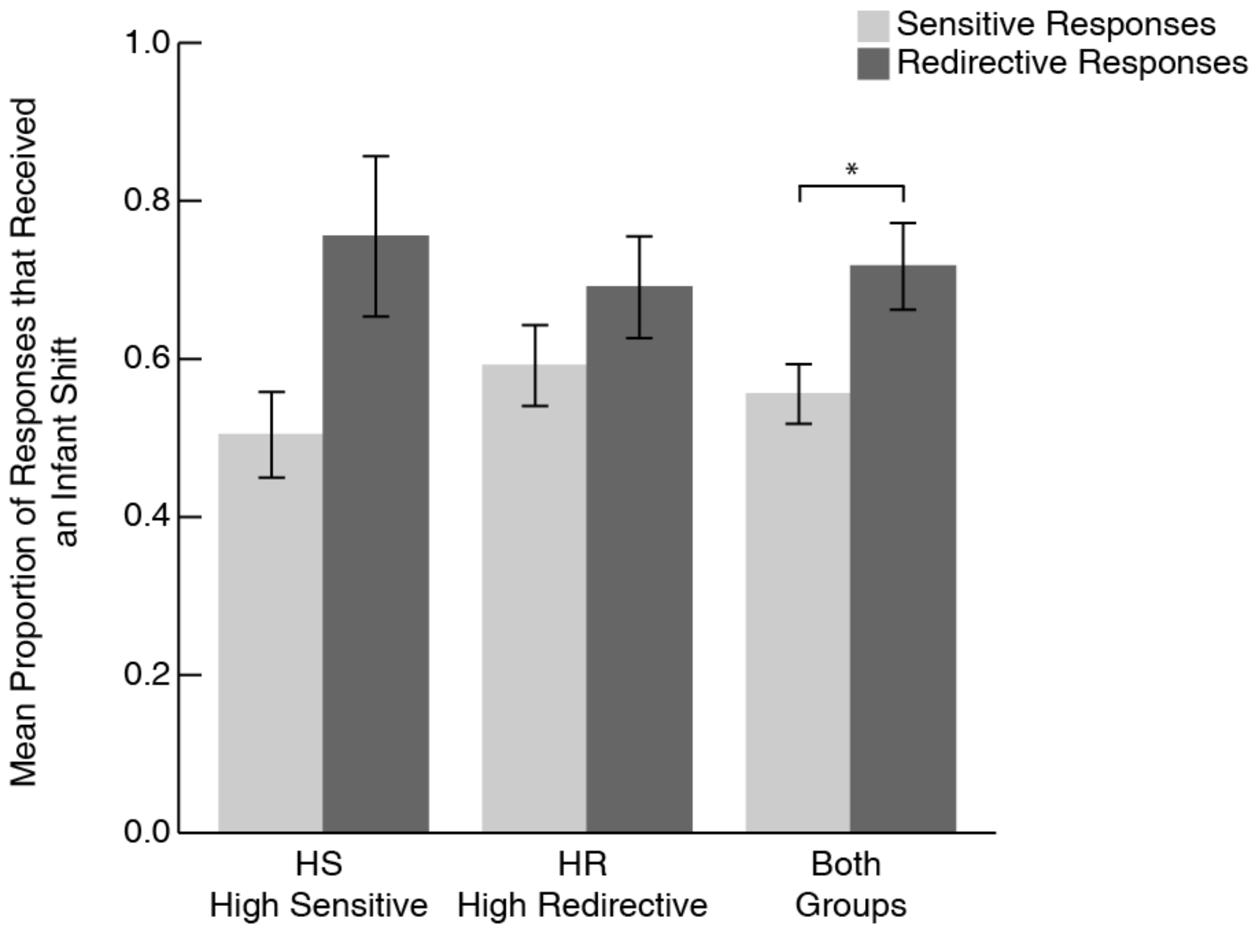


*Figure 1.5*. Graph depicting the effects of response type (either sensitive or redirective responses) on all infants' likelihood of shifting contingently to the response. Because the number of sensitive and redirective responses from which to sample differed robustly between HS and HR groups (for instance, two of the seven HS caregivers provided 2 or fewer redirective responses), we assessed the effects of sensitive and redirective responses across all dyads rather than between groups. Overall, infants were more likely to shift to a caregiver response when it was redirective compared to when it was sensitive. *p < .05

Next, we compared, between *HS* and *HR* caregivers, the total proportion of all contingent responses that elicited an infant attentional shift. Overall, infants of *HR* caregivers shifted gaze to a higher proportion of their caregivers' responses than infants of *HS* caregivers (mean *HS* = 52.35%, mean *HR* = 65.05%; $t(15) = -2.22$, p = .04; Figure 1.6). To examine the robustness of this effect, we next focused on infants' gaze shifting in reaction to *non-referentials* alone. Non-referential responses were exhibited at similar rates among both caregivers groups (*HS* mean rate of non-referential responses/minute: 3.07; *HR* mean: 3.41; $t(15) = -.48$, p = .64), and were thus unbiased by our group assignment. As before, infants of *HR* caregivers shifted to a significantly higher proportion of non-referential behaviors compared to infants of *HS* caregivers (infants of *HS* caregivers: 51.72%; infants of *HR* caregivers: 66.35%; $t(15)=-2.24$, p=.04; Figure 1.6).

*Content of infant reactions*. In addition to shift frequency, we also quantified the targets of focus that infants shifted to when they reacted to caregivers' responses (Supplemental Table S1.3). Of these reactions, we were primarily interested in infants' shifts to non-referentials, given that such responses did not contain any information intended to direct infants' attention to a particular location. The targets of *HS* and *HR* infants' reactions to non-referentials are shown in Figure 1.7. When infants of highly sensitive caregivers shifted on non-referentials, 46.44% of these shifts were to objects on average, followed by undirected areas (35.12% of non-referential shifts) and infants' caregivers (18.44% of shifts). For infants of highly redirective caregivers, 71.46% of their non-referential shifts were to objects, followed by undirected areas (16.48% of shifts), and lastly to caregivers (12.05%). To assess whether infants of *HS* and *HR* caregivers showed a significant bias for shifting to objects over their next highest looking category (i.e., undirected areas), and whether any biases differed between groups, we ran a 2 (caregiver group) x 2 (looking category: objects vs. undirected areas) mixed ANOVA[4] on the proportion of infants'

[4] Again, because the looking categories and their associated proportions are mutually exclusive, one looking category must be excluded in order to legitimize between-subjects comparisons among infants of *HS* and *HR*

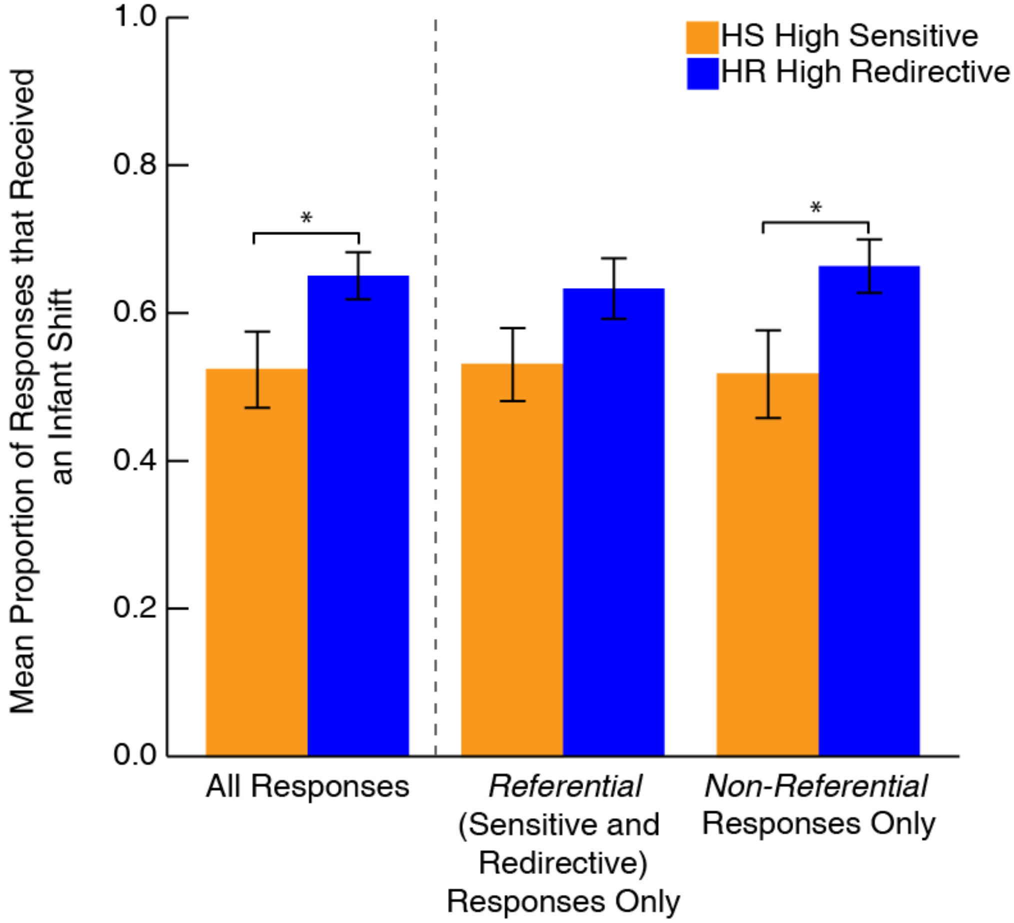


*Figure 1.6*. Graph depicting the proportions of caregiver responses that infants of highly sensitive (HS) and highly redirective (HR) caregivers shifted contingently in response to. The first group of columns illustrates infants' shifts towards all caregiver responses; the second group of columns depicts infants' shifts towards *referential* (sensitive or redirective) responses only; and, the third group of columns illustrates infants' shifts towards *non-referential* responses only. *p < .05

contingent shifts ending at either objects or undirected areas (Figure 1.7a). There was a significant main effect of looking category ($F(1,15)=33.77$, $p < .001$) as well as a significant looking category x caregiver group interaction ($F(1,15)=14.64$, $p = .002$), with no main effect of caregiver group ($F(1,15) = 1.075$, $p = .32$). Tests of simple effects revealed that infants of *HR* caregivers showed a strong bias to shift to objects compared to undirected areas in response to

caregivers. Thus, for our analyses, we excluded the looking category that infants shifted to the least on average, i.e., caregiver areas.

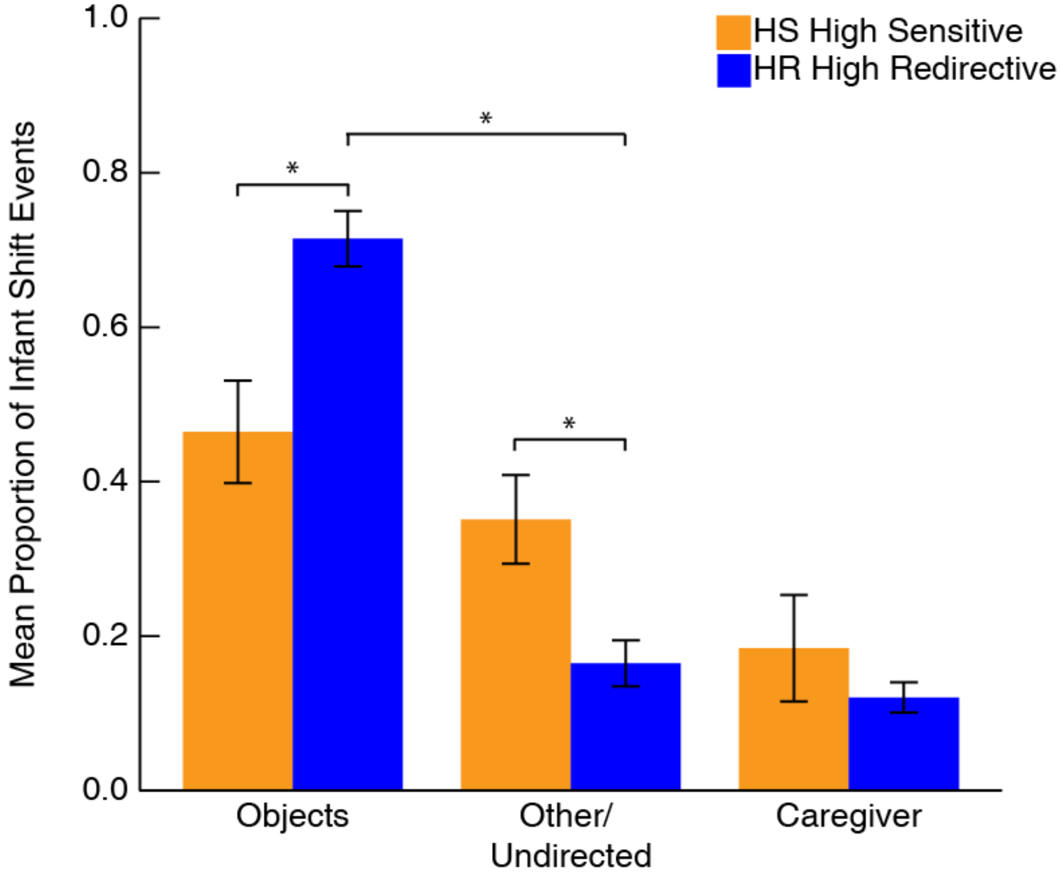


*Figure 1.7*. Visual targets of infant attentional reactions (shifts) in response to caregivers' *non-referential* responses. Orange bars denote mean proportions of shift events ending in each target for infants of highly sensitive caregivers; blue bars denote mean proportions for infants of highly redirective caregivers. *p < .05.

non-referentials ($F(1,9) = 76.15$, $p < .001$). Additionally, infants of *HR* caregivers shifted to objects at a significantly higher frequency than infants of *HS* caregivers during these events ($F(1,15) = 12.83$, $p = .003$). In contrast, infants of *HS* caregivers did not shift significantly more to objects over undirected areas in response to non-referentials ($F(1,6) = 1.21$, $p = .31$). Furthermore, infants of *HS* caregivers showed a greater frequency of shifts to undirected areas during these moments compared to infants of *HR* caregivers ($F(1,15) = 9.86$, $p = .007$).

To ensure that the differences observed in *HS* and *HR* infants' looking endpoints were not due to differences in what infants were attending to immediately prior to their caregivers' non-referential responses, we also examined the areas that infants were most recently attending to before receiving a non-referential response. Infants of both groups were most often attending to objects before receiving a non-referential response (mean *HS*= 64.21% of total occasions; mean *HR*= 73.91% of total occasions), and targeted comparisons revealed no significant between-groups differences in infants' attention to objects ($t(15) = -1.56$, $p = .14$) or to undirected areas (mean *HS* = 22.87%, mean *HR* = 9.71%; $t(15) = 1.97$, $p = .067$) prior to receiving a non-referential response.

## Discussion

We investigated how individual differences in social coordination among caregivers and their 5-month-old infants relate to differences in infants' early visual attention patterns. We focused on characteristics theorized to support the development of attention sharing and subsequent joint attention. Specifically, we assessed how opposing signal-to-noise ratios of contingent *sensitive* and *redirective* responding among caregivers correspond to differences in infants' attentional preferences toward socially-relevant stimuli, as well as infants' general attention span and reactivity to caregivers' social prompts. Though all infants spent the majority of their time looking at objects, infants of highly sensitive caregivers showed attention patterns that imply social attunement (Kuchirko et al. 2017). This attunement was apparent within these infants' looking preferences as well as the timing of their gaze shifts, which accommodated the content of their caregivers' responses. These differences in early looking patterns may have implications for later attention sharing and joint attention in social contexts.

Regarding attentional focus, infants of highly sensitive caregivers significantly preferred attending to caregiver-held objects over other objects across the social interaction. In contrast, infants of highly redirective caregivers did not show a preference for objects with which their caregivers were engaged, attending relatively equally to static (non-caregiver related) objects. Furthermore, when caregivers responded with non-referential behavior, infants of highly redirective caregivers showed a more fixed pattern of shifting to unrelated objects, while infants of highly sensitive caregivers exhibited more distributed gaze toward objects and other areas. These results suggest that the attentional patterns of infants of highly sensitive caregivers are more strongly organized towards social partners and associated objects than are those of infants of highly redirective caregivers. Crucially, these differing patterns of attention organization held even when caregivers produced non-referential behavior.

Along with differences in infants' focus, we also found relations between caregivers' response patterns and infants' moment-by-moment social reactions. Namely, infants of highly sensitive caregivers exhibited some evidence of being more sensitive to the content of their caregivers' responses than infants of highly redirective caregivers. This was most apparent in the fact that infants of highly sensitive caregivers were less likely to shift gaze in reaction to caregivers' non-referential responses than infants of highly redirective caregivers. Non-referentials were similar in structure among both groups of caregivers (i.e., overwhelmingly verbal; Supplemental Table S1.2), and by definition were not intended to support nor distract infants from their current focus. Thus, the fact that infants showed differences in shifting to these cues suggests that caregiver sensitivity and redirectiveness may also influence infants' reactivity towards more open-ended social behavior. Additionally, while *HS* and *HR* caregivers' redirections were equally likely to elicit a successful change in infants' focus, infants of highly sensitive caregivers were quicker to attend to their caregivers' occasional redirections than infants of highly redirective caregivers. This speed of attentiveness could in part be explained by these infants' overall sensitivity toward their caregivers' held objects (Figure 1.3b), as caregivers' redirections often involved manual/multimodal cues (Supplemental Table S1.2). Another possibility is that infants of highly sensitive caregivers have learned that their caregivers' responses are most often aligned with infants' own focus, and are thus more inclined to "infer" that their caregivers' occasional redirections will be predictive of something interesting as well. Whether or not *HS* caregivers' redirections are actually more predictive of infants' interests than those of *HR* caregivers remains to be determined. Nonetheless, our results taken together indicate that infants of highly sensitive caregivers may be more selectively attuned to their caregivers' social cues than infants of highly redirective caregivers. Such selectivity may be a precursor to the specificity of vocal, gestural, and affective responding that older infants exhibit during communicative exchanges with adults (e.g. Kuchirko et al 2017; Beebe et al., 2010), though further longitudinal research is needed to explore this possibility further.

Until recently, studies of social attention development have often assessed infant looking in isolation, using highly controlled paradigms to investigate whether and when infants prefer to look at social stimuli (Johnson, Dziurawiec, Ellis, & Morton, 1991; Jones & Klin, 2013; Wilkinson, Paikan, Gredebäck, Rea, & Metta, 2014). Additionally, "social stimuli" have often been restricted to mean images of human faces and eyes (Johnson et al., 1991; Jones & Klin, 2013; Wilkinson et al., 2014; though see also Klin, Lin, Gorrindo, Ramsay, & Jonas, 2009). Newer work has expanded the notion of social stimuli, to include other sights and cues that are predictive of caregiver engagement in more naturalistic settings (Miller et al. 2009; Deak, Krasno, Jasso, & Triesch 2018; Deák et al., 2013; Yu & Smith, 2013, 2016, 2017). Such work has shown that social attention may arise through multiple pathways, including through infants' attention to objects that their caregivers are holding or touching. The current study builds upon this line of research, to describe how individual differences in caregiver behavior might relate to differences in infants' levels of hand-object social attention. We found that only infants of highly sensitive caregivers preferred attending to their caregivers' held objects at 5 months of age. Though the question of causality remains open, our present findings may mean that high SSNRs of sensitivity strengthen hand-object pathways of joint attention development early on, which may in turn have implications for later communicative learning (e.g. Gogate, Bolzani, & Betancourt, 2006).

Current theories of joint attention development have also suggested that differences in physiological arousal and vigilance during infancy may contribute to differences in attention sharing. Specifically, heightened arousal presumably corresponds to increased gaze shifting (shorter look durations; de Barbaro, Clackson & Wass 2017) and less social cue following, as infants' attention is driven mainly by exploration of new sights and less by exploitation of predictable cues (Deák et al. 2013). In experimental settings, infants showing higher behavioral indices of arousal tend to shift more frequently and attend more to salient distractors over social cues (de Barbaro, Chiba, & Deák, 2011). Furthermore, shorter fixation durations in infants (an index of heightened arousal) have been associated with later characteristics of autism, including social-communicative difficulties (Wass et al., 2015, though see also Colombo, Shaddy, Richman, Maikranz, & Blaga, 2004). In the present work, we found that while infants of highly redirective caregivers showed only a trend toward increased shifting overall, they were significantly more reactive to caregivers' non-attention directing (non-referential) responses than infants of highly sensitive caregivers. Additionally, infants of highly redirective caregivers were slower to attend to caregivers' attention-directing prompts (redirections) than infants of highly sensitive caregivers. Thus, our findings lend partial support to the possibility that infants of highly redirective caregivers are exhibiting behavioral signs of hypervigilance relative to infants of highly sensitive caregivers, and are partially in line with experimental work indicating that redirective adults cause infants to be more distractible (Miller et al. 2009). Further replications of our findings, presumably with a larger sample size, will be needed to further delineate relations between caregiver sensitivity/redirectiveness and infant arousal.

While our microstructural approach to assessing caregivers' behaviors and infants' attention patterns is a strength of the current study, some limitations should be noted. First, while our broader caregiver sample was of sufficient size for our initial observations of caregiver behavior, these caregivers exhibited a limited range of redirective behaviors (Figure 1.2), making it difficult to assess how marked SSNRs of redirective behavior relate to differences in our infant attentional measures. This limitation is likely a consequence of the homogeneity of our caregiver sample generally, the majority of whom were well-educated, high social economic status (SES) families. Such homogeneity limits our ability to generalize our findings to more at-risk caregiver groups, including samples with lower SES. Additionally, the fact that even our most redirective caregivers often exhibited a high or "middle range" proportion of sensitive responses greatly restricted our sample size for infant attention analyses, given our interest in targeting infants of caregivers with highly contrasting SSNRs of sensitivity and redirectiveness. Future work should make efforts not only to explore the levels of redirectiveness and sensitivity observed in a broad range of caregiver groups from different backgrounds, but also to assess how these differing proportions of responsiveness might relate, on a more continuous level, to differences in infant attention.

Two types of data will be needed to further explore and expand upon our interpretation of our findings. First, we must compare the effects of SSNR with those of sensitivity and redirectiveness. In curiosity-driven learning (Oudeyer & Smith, 2016), the ability to predict outcomes and reduce uncertainty motivates infants to repeatedly engage with objects and stimuli surrounding them. Extending this idea to the social domain, both the timing and content of caregivers' responses may contribute varying levels of predictable structure to encourage infants' engagement. Sensitive responding may be associated with greater predictability, as caregivers' responses are controlled by the infant's own focus of attention. Sensitive responding may also reduce uncertainty regarding the objects that infants are currently exploring, as caregivers' engagement with these objects may provide more information about their affordances and properties. Such predictability may be the mechanism driving infants' attentiveness toward highly sensitive caregivers' social cues. However, infants' attentiveness might be further driven by the structure of caregivers' response timing. For instance, infants may more able to predict that their caregivers' social cues are reliably sensitive if caregivers are also highly contingent, i.e., if they also respond promptly and frequently to infants' behaviors. Additionally, caregivers who are highly contingent and redirective may be more predictable (and thus perhaps more motivating) than caregivers who are highly redirective but who also do not respond reliably to infants' behaviors. As the caregivers in our targeted sample were fairly similar in their rates of contingent responsiveness, the present study did not differentiate between highly contingent and less contingent patterns of caregiver sensitivity and redirectiveness. However, experimental work in our laboratory is currently exploring how differing levels of contingency and of sensitivity/redirectiveness might interact to predict differences in infant looking, arousal, and motivation to attend to social cues. Follow-up work should also investigate how infants' preferences for predictable caregiver behavior changes over development and learning, if predictability is in fact found to be a primary factor underlying infants' social attention patterns.

Secondly, future work must address the issue of causality, and explore more intensively the bidirectional relations between caregiver responsiveness and infant attention differences. While differences in parental sensitivity and redirectiveness might create individual differences in social attunement, early differences in infants' patterns of attention might reciprocally shape how caregivers respond. For example, infants who have shorter attention spans early in development might prompt caregivers to redirect their attention more frequently. In turn, more redirections could cause increased gaze shifting and arousal, which would also influence infants' attention to social cues. Alternatively, longer looking during infancy might provide caregivers with more opportunities to provide sensitive feedback. Sensitive responding in turn could encourage sustained attention as well as attention to caregivers' subsequent social cues. Current research in our laboratory is working to tease apart the question of causality by examining short-term effects of experimenter-controlled sensitivity and redirectiveness on infant attention in social interactions. Additionally, future longitudinal analyses in our lab will examine how caregivers' response structures change over development (Bornstein et al., 2008), and whether such changes correspond to differences in infant attention as well as later social and communicative outcomes.

We hope that the current study will provide a first step in connecting individual differences in dyadic coordination with differences in early infant visual patterns associated with later attention sharing. While further investigation and replication with larger samples is necessary, our findings indicate that differences in contingent sensitivity and redirectiveness relate to infant attention differences in social contexts as early as 5 months of age. Such differences in early attention patterns, as well as in predictive learning, are increasingly recognized as key components of neurodevelopmental conditions (Sinha et al., 2014). We thus anticipate that our observations may be combined with future work to inform our knowledge of the specific social structures important for attention development, as well as interventions aimed at improving overall attention and attention sharing among at-risk infants and children.

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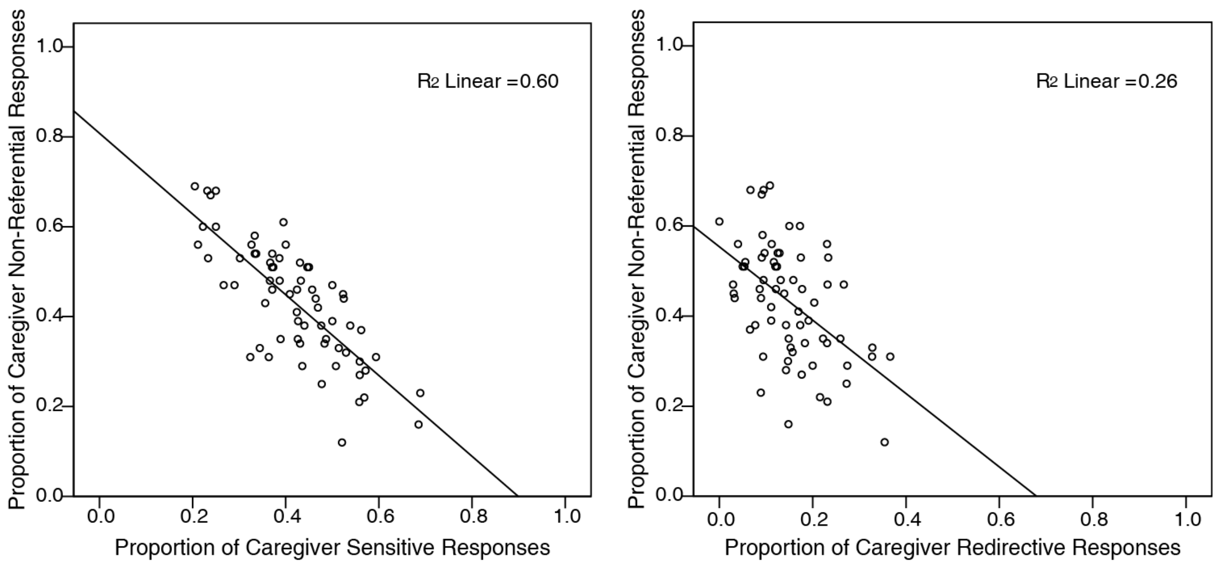
**Supplemental Figures and Tables for "The role of dyadic coordination in organizing visual attention in 5-month-old infants":**




*Supplemental Figure S1.1.* Relations between caregiver sensitive and redirective response types, and caregiver non-referential responses for entire caregiver sample (N=67). As shown above, both sensitivity and redirectiveness negatively correlated with the proportions of non-referential responses caregivers displayed, though (as observed in main text Figure 1c) sensitivity and redirectiveness levels among caregivers were not directly related to one another.

Supplemental TABLE S1.1.
Interrater Reliability Statistics for Individual Infant and Caregiver Variables

| Measure | Absolute ICC (single measures) | 95% Confidence Interval |
|---|---|---|
| ***Total time labeled "uncodable"*** | .85 | .64 - .94 |
| ***Total caregiver handling time coded*** | .99 | .97 - 1.00 |
| ***Infant relative looking times at caregiver, undirected areas, or objects during caregiver-engaged periods, raw times (% time)*** | .97<br>(.97) | .96 - .98<br>(.96 - .98) |
| ***Relative looking at engaged objects, raw times (% time)*** | .98<br>(.94) | .94 - .99<br>(.85 - .98) |
| ***Relative looking at unengaged objects, raw times (% time)*** | .95<br>(.93) | .87 - .98<br>(.82 - .97) |
| ***Infant relative looking times at caregiver, undirected areas, or objects during caregiver-unengaged periods, raw times (% time)*** | .99<br>(.99) | .98 - .99<br>(.985 - .994) |
| ***Infant shift rate across all periods*** | .76 | .57 - .87 |

Supplemental TABLE S1.2.
Modality Characteristics of Sensitive, Redirective, Non-referential, and All Contingent Responses Provided by Highly Sensitive (HS) and Highly Redirective (HR) Caregivers

| | Vocal-only (% of total) | | | Behavioral-only (% of total) | | | Multimodal vocal/behavioral (% of total) | | |
|---|---|---|---|---|---|---|---|---|---|
| | *HS* caregivers M*(SD)* | *HR* caregivers M*(SD)* | *t(15)* | *HS* caregivers M*(SD)* | *HR* caregivers M*(SD)* | *t(15)* | *HS* caregivers M*(SD)* | *HR* caregivers M*(SD)* | *t(15)* |
| *Sensitive* responses | 53.34% (22.64%) | 38.70% (15.69%) | 1.58 | 13.05% (9.30%) | 14.05% (9.20%) | -0.22 | 33.60% (15.57%) | 47.25% (10.89%) | -2.14[+] |
| *Redirective* responses | 27.10% (25.35%) | 14.25% (8.36%) | 1.29[a] | 34.64% (14.45%) | 33.43% (14.26%) | 0.17 | 38.27% (28.21%) | 52.32% (10.47% | -1.26[a] |
| *Non-referential (other)* responses | 99.73% (0.73%) | 100% (0.00%) | -1.00[a] | 0.00% (0.00%) | 0.00% (0.00%) | n/a | 0.27% (0.72%) | 0.00% 0.00% | 1.00[a] |
| ***All* contingent responses** | 66.36% (18.90%) | 57.45% (8.80%) | 1.16[a] | 10.29% (6.83%) | 13.42% (5.58%) | -1.04 | 23.36% (13.28%) | 29.14% (6.61%) | -1.19 |

[a]For cases in which Levene's test was violated, Welch's corrected t-test was used
+p= .050

SUPPLEMENTAL TABLE S1.3.
Composition of Infant Shift Types in Reaction to Caregivers' Contingent Sensitive, Redirective, and Non-referential Responses

| | Infant shifts to *objects* (% of total reactions) | | Infant shifts to *caregiver* (including hands) (% of total reactions) | | Infant shifts to *undirected areas* (% of total reactions) | |
|---|---|---|---|---|---|---|
| | *HS* caregivers M*(SD)* | *HR* caregivers M*(SD)* | *HS* caregivers M*(SD)* | *HR* caregivers M*(SD)* | *HS* caregivers M*(SD)* | *HR* caregivers M*(SD)* |
| *Sensitive* responses | 55.16% (30.32%) | 72.83% (19.41%) | 23.41% (20.82%) | 12.99% (12.49%) | 21.43% (13.08%) | 14.18% (14.40%) |
| *Redirective* responses | 75.65% (37.73%) | 85.67% (10.02%) | 22.56% (37.99%) | 9.54% (9.53%) | 1.79% (4.73%) | 4.79% (6.28%) |
| *Non-referential (other)* responses | 46.44% (17.58%) | 71.46% (11.35%) | 18.44% (18.24%) | 12.05% (6.19%) | 35.12% (15.15%) | 16.48% (9.42%) |

# CHAPTER 2.

# USING INFANT EYE GAZE TO EXPLORE BIOLOGICAL MODELS OF SOCIAL INFLUENCES ON EARLY ATTENTION

Gina M. Mason, Michael H. Goldstein

Abstract

Infant visual attention has been widely studied within the field of development, though our understanding of the social and biological mechanisms underlying individual differences in looking and attention organization remains limited. Prior notions of infant looking have mainly been rooted either in a strictly information-processing perspective, in which differences in look durations are thought to reflect processing efficiency, or in some variation of the dual-process model, whereby look durations reflect both the arousing/sensitizing properties of the stimulus and the infant's current state, as well as infants' information-processing ability. In the present work, we aimed to build upon recent efforts to characterize infant looking behavior in terms of neurobiological theories of arousal, and propose that infant looking patterns are malleable in the face of recent social experiences. Using an adaptation of a previous attention paradigm described in de Barbaro, Chiba, & Deák (2011), we explored whether behavioral measures of arousal defined in prior neurobiological literature correlated with one another within the framework of infant looking. Among eighty 6-7-month-old infants, we found strong correlations between measures of fixation durations, orientations to salient stimuli, target fixations, and fixation rates, replicating de Barbaro et al.'s (2011) previous findings. Prior to completing the attention task, infants also participated in a social interaction with a novel social partner, who responded to infants' looks and vocalizations under one of four response schedules that varied in levels of overall contingency, sensitivity (joint focus) and redirectiveness (attempts to shift focus). We found that infants' proximal social experience predicted changes in arousal behavior on the attention task, with infants receiving "high contingency" (HC) response schedules showing lower vigilance patterns than infants receiving "low contingency" (LC) response schedules. Findings are discussed relative to current ideas regarding social influences on attention organization.

Using infant eyegaze to explore biological models of social influences on early attention

Individual differences in infant visual attention have long been of interest to developmental scientists. In particular, differences in infant looking patterns (often used as an indicator for early attention) have been regarded as a measure of information processing and arousal (Colombo, Frick, & Gorman, 1997; Groves & Thompson, 1970; Malcuit, Pomerleau, & Lamaree, 1988), as well as a predictor of later cognitive and neurodevelopmental outcomes (Colombo, Shaddy, Richman, Maikranz, & Blaga, 2004; McCall & Carriger, 1993; Wass et al., 2015). Considering how individual differences may arise, current theories of development propose that the determinants of individual difference are complex and dynamic, as infants both regulate and are co-regulated by changes in their intrinsic biology, the behaviors they generate, and the external feedback they elicit and receive from their surrounding environment (Byrge, Sporns, & Smith, 2014;Gottlieb, 2007; Sameroff, 2009). Specific to attention development, various processes at different levels of explanation have been evoked to describe individual differences in attention, ranging from differences in the functioning of specific brain structures (e.g. Friedman, Watamura, & Robertson, 2005; Mercuri et al., 1997) to differences in neuromodulator and stress hormone regulation (de Barbaro, Clackson, & Wass, 2017; Tu et al., 2007) and to variability in early caregiving and economic environments (Blair et al., 2011; Thompson & Trevathan, 2008; Tu et al., 2007). Though recent studies have attempted to draw connections between these levels of analysis either conceptually (de Barbaro et al., 2011) or through explicit multivariate studies (e.g. Blair et al., 2011; de Barbaro, Clackson, & Wass, 2017; Tu et al., 2007), many questions remain unanswered regarding how early external environments and biology mechanistically interact to generate changes in early attention across development.

Regarding external influences on infant visual attention organization, arguably one of the most prominent elements of infants' early environments is the presence of adult caregivers. Accordingly, differences in aspects of social interaction and coordination between infants and caregivers have been widely studied, and have been related longitudinally to a number of learning and attentional outcomes as well as to differences in child physiology (Baumwell, Tamis-LeMonda, & Bornstein, 1997; Blair et al., 2011; Landry, Smith, Swank, Assel, & Vellet, 2001). However, the direction of causality is often tenuous within these studies, as it is unclear whether social interaction differences and attention/learning are directly related, or whether other unmeasured variables are moderating the relations observed. Additionally, though many longitudinal studies offer valuable insights into relations between early variables and later outcomes, they often do not provide information on the more immediate effects of early social interaction on infants' proximal visual attention organization. To evaluate possible causal influences of social feedback on attention then, it is necessary to augment longitudinal investigations with studies that measure real-time effects of well-defined social behaviors on infants' attention. When possible, such studies should also endeavor to connect their paradigms to biological models (e.g. de Barbaro et al., 2011), so as to build a more comprehensive understanding of tangible mechanisms underlying social influences.

*Cognitive and Biological Accounts of Early Attention: Information-Processing & Arousal*

While defining the neurobiology of visual attention is an ever-evolving process (for reviews, see Aston-Jones & Cohen, 2005; Carrasco, 2011; and Noudoost & Moore, 2011), many infancy researchers have historically focused on a small set of primary frameworks when describing neurocognitive processes underlying infants' looking behavior. In one framework, the durations of infants' fixations are explained in terms of information processing (IP), whereby infant looking denotes active encoding and building of a memory trace for the stimulus being viewed. The notion of looking as information processing was originally adapted from a neurobiological comparator theory described by Sokolov (e.g. 1963), who, in interpreting work measuring attentional orienting in non-human animals, proposed that the responses of a specific set of neurons guiding attention (*comparator neurons*) would be attenuated once the response patterns of *afferent neurons* (neurons that always fire for the stimulus, even across repeated exposures) and *extrapolatory neurons* (neurons that only fire for a stimulus after extensive exposure) began to align with one another. In this model then, reductions in attentional orienting (via reductions in comparator neuron firing) were taken to indicate that the properties of the stimulus had been encoded and stored in memory. Though Sokolov's (1963) model was not necessarily intended to explain overt looking behavior *per se*, developmentalists using infant looking as a proxy for attention subsequently employed Sokolov's framework as a means of describing the processes underlying infants' visual fixations (Colombo & Mitchell, 1988, 1990). Specifically, infant looks were theorized to embody information gathering, and decreases in infants' look durations over time or repeated exposure to a stimulus were hypothesized to reflect successful encoding and completion of a stimulus representation. Individual differences in looking times then were hypothesized to reflect differences in infants' efficiency of information processing, meaning that shorter/faster lookers were considered more advanced compared to long lookers (Colombo, Mitchell, Coldren, & Freeseman, 1991)

Since its initial introduction, the IP perspective of infant looking has been revised and modified over the decades, as many researchers have challenged the view that infant looking only reflects information processing (Colombo et al., 1997; de Barbaro et al., 2011; Groves & Thompson, 1970; Schöner & Thelen, 2006; Velden, 1978). Among these critiques is the observation that infants' looking times can vary across different contexts, and also that infants' baseline arousal levels (as well as the contextual relevance of a stimulus) may activate different patterns of looking to stimuli of approximately equal structural complexity (de Barbaro et al., 2011; Velden, 1978). Considering the role of arousal in visual attention broadly, early and recent work in non-human animals supports the notion that neural and physiological systems modulating arousal, including the locus-coeruleus noradrenergic system (LC-NE) and the peripheral sympathetic nervous system, may influence differences in attention and subsequent behavior (Aston-Jones, Rajkowski, & Cohen, 1999; Aston-Jones & Cohen, 2005; Bunsey & Strupp, 1995; Oken, Salinsky, & Elsas, 2006; Rajkowski, Kubiak, & Aston-Jones, 1994). Specifically, low levels of noradrenergic activity/low tonic LC-NE firing correspond to relative non-alertness and inattentiveness, and are typically associated with "drowsy" behaviors such as sleeping or resting. In contrast, mid-range noradrenergic activity (high phasic and moderate tonic LC-NE firing) is associated with focused and flexible attentiveness, in which an animal can exploit and maintain focus on task-relevant stimuli while avoiding compulsive responses to salient distractors. Finally, high noradrenergic activity/high tonic LC-NE firing corresponds to high exploration, distractibility and hypervigilance, whereby the animal frequently responds to salient distractor stimuli in addition to (or perhaps in contrast to, depending on the circumstance) task-relevant cues.

To test whether arousal-based accounts of attention help to explain specific aspects of infant looking behavior that were previously unaddressed by the IP perspective, researchers have subsequently developed paradigms that explore whether certain relations exist between looking behaviors that are predicted to coincide under the LC-NE model. For instance, de Barbaro and colleagues (2011) developed a novel vigilance task (we refer to it throughout this article as the Cued Attention task) based on previous gaze-and-point paradigms (e.g. Deák, Flom, & Pick, 2000), in which infants were surrounded in a room by computer monitors that played different 8-sec audiovisual animations one by one. Each animation was highly salient and approximately equally matched in stimulus complexity, and an adult social partner was also present to guide the infant's attention after a delay following each animation onset. From behaviors observed in the animal literature, de Barbaro et al. (2011) predicted that if infants' looking was modulated by arousal, then infants who tended to have *many short scanning looks* around the room (a behavioral sign of high arousal) would be expected to *attend more overall* to the highly salient and distracting audiovisual animations across trials, and also to *orient more quickly* to the audiovisual animations than infants who did not have as many short broad-scanning fixations. Additionally, while the information-processing model would predict infants' looking times to be approximately equal and stable for each animation given the animations' approximately matched complexity, the LC-NE model predicted that infants' attention to each new stimulus would vary as a function of time and arousal level, with low arousal leading to more flexibility and variation in stimulus looking than high arousal (which would theoretically lead to a high degree of hyperattentive looking, or *hypervigilance*, across animations). The predictions made by the LC-NE model were in fact supported, as all of the behavioral signatures of arousal assessed (rate and duration of scanning fixations, latency to orient to animations, and likelihood of attending to each animation) correlated strongly with one another. Additionally, infants showing higher behavioral signs of arousal (as measured via a standardized composite of the vigilance measures above) attended more consistently (and for more total time) to the salient animations, while infants showing low arousal fluctuated significantly in their looking to the animations as each trial progressed. Taken together, the results of this study indicate that the neurobiological processes regulating infant visual attention likely include arousal-based systems, which may interact with other encoding and memory systems to allocate attention flexibly and adaptively in dynamically changing contexts (Gary Aston-Jones & Cohen, 2005).

*Social Influences on Infant Arousal and Attention*

Reviewing the above results in the context of individual differences, de Barbaro et al.'s (2011) findings help to establish that differences in visual attention and looking behavior among infants may not simply reflect differences in efficiency of information processing, but that they may also (or rather) indicate differences in transient or more consistent arousal regulation. Given that differences in caregiver-infant interactions have previously been associated with differences in infants' affective arousal (e.g. Feldman, 2003; Gable & Isabella, 1992), might specific features of adult-infant social interaction also affect changes in arousal-based attention organization among infants? And if so, which features are most predictive of individual differences?

Recent work assessing caregiver-infant interactions have suggested that two main facets of caregivers' behavior appear to predict a wide range of both short and long-term differences in infant learning and attention. One of these facets is the timing, or *contingency*, of caregivers' actions relative to infants' own behaviors. For instance, both experimental and observational studies have shown that when caregivers respond within a prompt and structured timeframe to infants' prelinguistic vocalizations, infants are more likely to learn phonological characteristics of their caregivers' speech (Goldstein & Schwade, 2008), as well as associations between visual and auditory referents (Goldstein & Schwade, 2009; Goldstein, Schwade, Briesch, & Syal, 2010). Additionally, caregivers' temporally-coordinated responses to infants' visual focus promote extensions of infants' visual attention (Yu & Smith, 2016) as well as, under certain conditions, enhanced word-object learning (Yu & Smith, 2012). Perhaps most relevant to the current study however, experimental manipulations of adults' contingency have also been shown to produce differences in infants' proximal performance on habituation and attention-based tasks. Specifically, when compared to infants on matched noncontingent (yoked-control) schedules, infants receiving contingent responses to their vocalizations have exhibited increased sensitization to nonsocial audiovisual stimuli presented within the subsequent minutes following the interaction (Dunham, Dunham, Hurshman, & Alexander, 1989). These findings suggest that in addition to promoting learning, contingent responding to infants' behaviors may also affect infants' consequent attentional engagement, including infant looking patterns that may be moderated by differences in arousal (Groves & Thompson, 1970).

Alongside the timing of adults' social responses, many studies have also focused on the *content* of such responses when drawing connections between social interactions and early attention development. Though precise operationalizations of social response content vary across different studies and techniques (see Mesman, 2010 for brief commentary), many researchers have converged on terms such as *sensitivity* and *redirectiveness* when describing adult interaction behaviors that either follow infants' current focus of attention (sensitivity) or attempt to distract infants from their current focus (redirectiveness). When assessed on a microbehavioral level, differences in social partners' sensitivity have been correlated with longitudinal differences in language development (Baumwell et al., 1997) as well as with differences in infants' moment-by-moment social attention and imitative learning (Mason, Kirkpatrick, Schwade, & Goldstein, 2018; Miller & Gros-Louis, 2017). Experimental studies have also related redirective responding to differences in infants' visual attentiveness and distractibility during social interactions (Miller, Ables, King, & West, 2009), and direct comparisons between infants receiving high proportions of sensitive vs. redirective responses have additionally revealed differences in infants' social looking during caregiver-infant interactions (Mason et al., 2018; Miller & Gros-Louis, 2013). While the above studies are compelling, it is currently less known how differences in social partners' response content might affect infant attention at different levels of overall contingency. Furthermore, though many of the studies assessing adults' response content have related content differences to differences in infants' simultaneous looking and learning, it is not as clear whether differences in content might also produce changes in arousal that carry over into subsequent attention-demanding tasks. These unresolved questions help to elucidate the impetus for our current investigation.

Reflecting briefly on how contingency and content might interact to produce differences in infant arousal, it may be helpful to consider the type of structure that these features of adult responding may provide for an infant in the context of predictive value. According to information-seeking and curiosity-driven learning perspectives (e.g. Gottlieb, Oudeyer, Lopes, & Baranes, 2013; Oudeyer & Smith, 2016), infant activities that facilitate learning are theorized to be intrinsically rewarding insofar as they assist in reducing uncertainty. Along these lines, studies have suggested that infant arousal and attention is most driven and engaged by stimuli that, based on prior experience, are neither too simple (already known or very easily decipherable) nor too complex or unlearnable (i.e., the "Goldilocks effect"; Kidd, Piantadosi, &

Aslin, 2012). Considering these principles in the context of adults' social feedback to infants, it is possible that high levels of contingency to infants' behaviors may allow infants to learn more readily that certain actions will produce reliable social effects (i.e., a response from an adult social partner), which can in turn help to reduce uncertainty and increase infants' ability to control the timing and amount of social stimulation that they receive. Indeed, there is evidence to suggest that infants learn relatively early on that their own behaviors, such as vocalizations, should elicit responses from caregivers within a reliable timeframe (Goldstein, Schwade, & Bornstein, 2009), and that infants find it relatively aversive when adult social partners deviate from responsiveness norms (Mesman, van IJzendoorn, & Bakermans-Kranenburg, 2009).

Regarding the effects of *content* within contingency however, it is also possible that differences in content (sensitivity vs. redirectiveness) may contribute differentially to infants' perception of predictability and uncertainty as well. For example, if the responses that a social partner provides are highly contingent and primarily sensitive, infants may more easily learn to predict not only *when* their social partner will respond to them, but also *where* and/or *what* their social partners' response is likely to be allocated toward (given that sensitive responses are aligned with what the infant is focused on). Such social feedback (high contingency and high sensitivity) could be considered the "most predictable" of all possible patterns of adult social responsiveness, and may perhaps promote lower subsequent arousal and lower explorative behavior (i.e., higher "exploitation"; Aston-Jones et al. 2005) than other less predictable response patterns. In contrast, if social partners' responses are primarily redirective, the object or area that social partners are referring to may be less predictable for the infant, and their responses overall may contain information that is not as readily accessible given the lack of coordination in attention between the adult and infant. Even if a primarily redirective social partner is highly contingent, if redirectiveness is perceived as undesirable or unpredictable in content by the infant, then high contingency could potentially have a paradoxical effect on arousal by sensitizing the infant to anticipate the social partner's response. Alternatively, high contingency may counteract the effects of high redirection by allowing infants to learn that their social partner's behaviors are "predictably unpredictable", in turn reducing uncertainty on a broad level while also possibly reducing infants' incentive to continue attending to their social partner's cues. In any case, as differences in environmental uncertainty and predictability have been associated with both short-and long term effects on stress regulation and behavior across species (Brumbach, Figueredo, & Ellis, 2009; Ulyan et al., 2006; though see also Miller, 1982), it is thus possible that the interacting contributions of contingency and content to the predictability of adult social partners' actions may differentially affect arousal and consequent attentional engagement among infants.

*The Present Study*

In the present work, we aim to explore whether specific features of adult social behaviors during adult-infant interactions produce changes in infants' subsequent looking behavior in an unrelated attention task, and whether the changes produced correspond to predictions made by certain biological models of attention regulation proposed in neuroscience. Specifically, we posit that differences in the timing (contingency) and content (sensitivity or redirectiveness) of adults' behaviors will influence changes in infants' arousal and vigilance state, as modulated by the locus coeruleus-norepinephrine system and other secondary systems involved in arousal regulation (Gary Aston-Jones & Cohen, 2005; Sapolsky, Romero, & Munck, 2000). As it is difficult to gain direct measures of such arousal changes in human infants, we use visual behavioral indices of increased arousal and vigilance as defined in previous attention paradigms (de Barbaro et al., 2011) to determine how experimentally-controlled social interactions may affect infant arousal. By doing so, we hope to gain clearer insights into causal mechanisms underlying social influences on early attention regulation and learning.

## Method

### *Participants*

To assess the effects of novel social partners' responsiveness on infant vigilance, we obtained data from a sample of eighty 6-7-month-old infants (39 female, 41 male; mean age 203 days, range 185-217 days). These infants and their caregivers were recruited via local birth announcements, flyers distributed to new parents at the city's local medical center, and other community outreach events taking place in Ithaca, NY. Fifty-three additional infants were tested, but were excluded due to: 1) technical error(s) during the Cued Attention (vigilance) task (n=12); 2) excessive infant fussiness during the social interaction and/or Cued Attention task (n=14); or, 3) failure of the experimenter to reach minimum response criteria (described in *Coding* below) during early piloting of experimenters' contingent sensitive and redirective response schedules (n=27). Of the eighty dyads included in our study, 79 completed the demographic survey, with one caregiver declining to give the age of herself and her partner. Caregivers' mean ages were 33.58 years (primary caregiver; range 20-46 years) and 35.04 years (partner/spouse; range 19-64 years). Approximately 76.25% of caregivers identified as White, Non-Hispanic, with the remaining 23.75% identifying as Chinese (10.00%), Japanese (2.50%), Asian-Indian (2.50%), African-American (1.25%), Costa Rican (1.25%), Indonesian (1.25%), and Biracial (5.00%). All but 2 primary caregivers had at least some postsecondary education at the time of the study, with approximately 90.1% holding a Bachelor's Degree or higher.

Along with quantifying the effects of experimenters' social response patterns on infants' vigilance using the Cued Attention task, we also examined infants' moment-by-moment attention patterns *during* their social interactions with experimenters. To explore infants' social attention, we selected a subset of 40 infants from the original 80 usable participants. This subset was selected semi-randomly, under the following constraints: the 40 infants were taken equally from each of four experimental response schedules, such that there were 10 infants per experimental group (for more details on the four response schedules, see *Procedure* below); and, infants between groups were equally matched on sex (i.e., 5 male and 5 female in each group).

*Materials/Apparatus*

During the study, all experimental activities, as well as infants' baseline social interactions with their own caregivers (see *Procedure* below), took place in a 12 x 18 foot playroom mounted with 3 Sony® DCR-TRV900 camcorders (Figures 2.1a-c). During infants' experimental social interactions, the playroom was divided into two separate areas. One half of the room was designated for the Cued Attention task, while the other half was arranged for naturalistic play (Figure 2.1b). This setup allowed for us to complete the Cued Attention task as soon as possible following the social interaction, so that the effects of our experimental social manipulation on infant arousal could be captured with minimal decay time (Davis & Granger, 2009; Dunham et al., 1989). For infants' baseline social interactions with caregivers as well as for their interactions with experimenters, a small white tub containing three types of toys (a ring stand containing removable stacking rings, a set of "Stack and Roll" stacking cups, and a soft plastic wire ball; Figures 2.1 a-b) were made available for exploration and play. Additionally, a circular play mat was placed towards the front of the room, and a large blue ergonomic pillow was available to support infants' sitting postures. Infants' vocalizations were recorded using a wireless microphone and transmitter (Telex FMR 500), which was concealed in a pair of customized infant-sized overalls worn by infants during the study. Caregivers' verbal prompts during baseline, and experimenters' responses during the experimental social interaction, were recorded using a separate wireless lapel microphone and transmitter (Telex FMR 1000).

For the experimental social interactions specifically, other materials included a set of wireless headphones, which the social partner wore to receive moment-by-moment response instructions from another experimenter (the "director") observing from an adjacent room. Caregivers, who were in the playroom with their infants during the experimental interaction, additionally wore a set of sound-attenuating headphones playing music. These headphones were used to encourage minimal systematic interference from the caregiver during the experimental interactions.

Regarding the Cued Attention task, all materials and procedures were based closely on the vigilance task reported in de Barbaro et al. (2011). Six standard 19-inch flat screen computer monitors, each outfitted with a stereo speaker and a Sony Handycam digital camcorder, were placed around the room in specific locations relative to the infant's position (Fig. 2.1c): three on the left side (one in the front, one to the side, and one further behind and diagonally facing the infant), and three to the right of the infant, in approximately symmetrical positions. An additional camera with a wide-angle lens was placed above the monitor displays, to capture additional infant gaze behaviors in locations not facing the monitor angles. To ensure minimal distraction

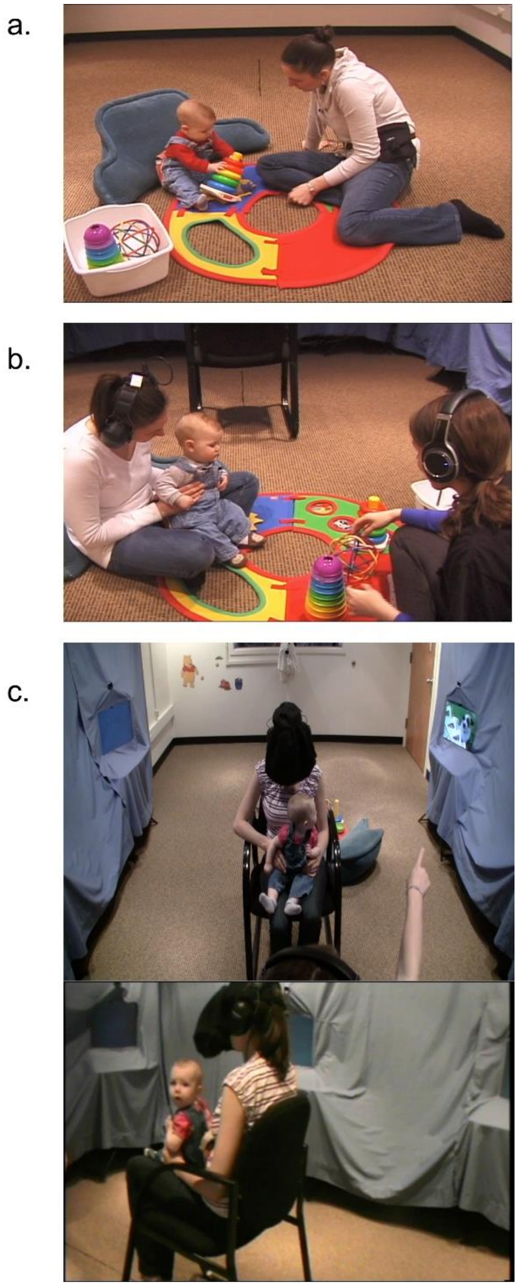



*Figure 2.1*. Experimental setup. a) Illustrates session 1 (familiarization), in which caregivers and infants engaged in an unstructured free-play interaction in our laboratory playroom on a day prior to the experimental interaction. b) Depicts the experimental social interaction occurring during session 2, which was immediately followed by c) the Cued Attention task, also occurring in session 2.

due to visible aspects of the setup itself (i.e., the presence of speakers, wires, table stands for the monitors, etc.), a set of blue curtains (with holes for the camera lenses and monitor screens) covered the walls and consoles such that only the monitor screens and camera lenses were visible to the infant. When monitors were not playing stimuli, they displayed a blue hue that allowed them to blend approximately with the background curtains (this hue was chosen during piloting to be the least “attention-grabbing” relative to brighter hues). Throughout the task, infants sat unrestrained on their caregiver’s lap, in a chair placed in the middle of the monitor displays and facing an experimenter (Figure 2.1c). The stimuli used in the task were identical to the 6 audiovisual animations used in de Barbaro et al., 2011, and were modified originally from “Baby Einstein”. During trials, caregivers wore a set of sound-attenuating headphones playing music, as well as an opaque black visor and veil, so as not to unintentionally prompt infants to react to the playing stimuli.

*Procedure*

All procedures were approved by the Institutional Review Board of Cornell University, and informed consent was obtained from all participating parent-infant dyads. The study took place over 2 sessions, occurring no later than 1 week apart.

**Session 1.** In session 1, infants and their caregivers participated in a 10-minute play session in our laboratory playroom with the toys described above (*Materials/Apparatus*). Caregivers were given no specific instructions on how to interact with their infants, but were simply told to play with their infants as they would at home. This session allowed infants to become familiarized with the toys used in the study, and for us to obtain future baseline data regarding individual infants’ attention patterns and caregivers’ levels of responsiveness.

**Session 2: Experimental Social Interaction and Cued Attention Task.** In session 2 of the study, infants first interacted for 10 minutes with an experimenter under one of four response schedules (described under *Response Schedules* below) approximating semi-naturalistic and diverse patterns of contingency, sensitivity and redirectiveness. These conditions were assigned between subjects, under the provision that the numbers of males and females assigned to each response schedule were matched when possible (i.e., three of the four conditions contained 10 males and 10 females, while one condition, *low contingency-high sensitivity*, contained 11 males and 9 females). Experimenters were given two interaction commands at a time in advance of their behaviors, and were instructed to respond (or not) as quickly as possible to noticeable fixations/shifts of gaze as well as infants' vocalizations. The director, who was providing commands to the experimenter, observed the interaction in another room via a two-way mirror, and was responsible for noting when the experimenter had completed their prior commands and were in need of additional prompts.

Immediately following the social interaction, infants participated in the Cued Attention task with a new experimenter, who was positioned in front of the infant and caregiver approximately at the infant's eye level. At the start of the task, the experimenter first attempted to bring each infant's attention to center by saying, "Hi, baby!" while directing her or his gaze to the infant's face. For each trial, one of the six surrounding monitors began playing one of the six possible 8-second audiovisual animations (video clips). Approximately 2 seconds after the start of the active (target) monitor, the experimenter simultaneously turned, pointed (with her adjacent arm and index finger), and shifted her gaze to the active monitor while prompting the infant verbally with the phrase, "Hey (baby's name), look!". The experimenter then maintained her/his gaze and point until the end of the clip. Immediately following the clip, the experimenter marked the end of the trial by dropping her/his arm, turning back to face the infant, and saying "Hi, baby!". An approximately 2-3 second silent inter-trial interval followed, and a new trial began with the start of the next monitor. Each infant completed a total of six trials, with each trial consisting of one active monitor and one 8-second video clip (with no repeated presentations). Order of monitor activation followed one of six counterbalanced schedules, and video clip order followed one of two counterbalanced schedules. The number of infants receiving each monitor/clip presentation order was matched across the four social interaction conditions.

*Response Schedules*

Experimenters' response schedules included crosses between *high* and *low* contingency (*high contingency (HC)*: experimenters were prompted to respond within 2 seconds to as many of infants' looks and vocalizations as possible; *low contingency (LC)*: experimenters were prompted to respond within 2 seconds to approximately 30% of infants' looks and vocalizations), and *high* and *low* sensitivity and redirectiveness (*high sensitivity/low redirectiveness (HS)*: approximately two-thirds *or more* of experimenters' responses were sensitive, and one-third *or less* were redirective; *high redirectiveness/low sensitivity (HR)*: approximately 2/3 *or more* of experimenters' responses were redirective, and 1/3 *or less* were sensitive). These crossovers produced 4 distinctive conditions: ***high contingency, high sensitivity***/*low redirectiveness* (*HCHS*); ***low contingency, high sensitivity***/*low redirectiveness* (*LCHS*); ***high contingency, high redirectiveness***/*low sensitivity* (*HCHR*); and, ***low contingency, high redirectiveness***/*low sensitivity* (*LCHR*). The contingency schedules employed are in line with previous experimental studies manipulating social responses to infants' behavior (e.g. Dunham et al., 1989; Goldstein & Schwade, 2008; Miller, Ables, King, & West, 2009), as well as with data on typical levels of caregiver contingency reported in prior studies (e.g. Bornstein & Manian, 2013; Gros-Louis, West, Goldstein, & King, 2006). Along similar lines, criteria for high/low sensitivity and redirectiveness were based on data from previous studies of of naturalistic caregiver-infant interaction in our laboratory (e.g. Mason, Kirkpatrick, Schwade, & Goldstein, 2018), which reported caregivers' mean level of contingent sensitive responding (calculated as a proportion of total contingent responses) to be approximately 41.92% (standard deviation= 11.17%). Using these data, we approximated "high" levels of sensitive responding (2 standard deviations above the mean) to be at least 64% of total contingent responses. While levels of redirective responding among caregivers were relatively minimal in comparison (prior study mean: 15.05% of all contingent responses, standard deviation= 8.09%), other experimental studies have employed higher rates of redirective behavior when exposing infants to interactions with novel social partners (i.e., Miller et al., 2009). Thus, experimenters in the present study were instructed to respond using schedules in which "high" and "low" levels of sensitive and redirective responding were defined equivalently, with "high" meaning approximately 2/3 or more of all contingent responses and "low" meaning 1/3 or less of all contingent responses.

During initial piloting of our experimenter response schedules, we found that experimenters had difficulty reaching the desired "high" threshold of sensitivity or redirectiveness (approximately 64% or more of all responses) when prompted to respond using 2/3 response schedules (appendix A1). Thus, we subsequently adjusted our response schedules to a 9/10 response schedule (appendix A2), which greatly increased the degree to which experimenters met or exceeded the 2/3 sensitivity/redirectiveness threshold. Sessions in which the 2/3 response schedule was used unsuccessfully were excluded and replaced, while sessions employing the 9/10 response schedule, as well as sessions in which experimenters approximately reached the high threshold using a 2/3 response schedule, were included.

*Coding*

Following data collection, researchers reviewed and annotated the session videos using ELAN, an open-source annotation software developed by the Language Archive at the Max Planck Institute for Psycholinguistics in Nijmegen (Sloetjes & Wittenburg, 2008; https://tla.mpi.nl/tools/tla-tools/elan/). Variables annotated for each task within the experiment are defined below:

**Cued Attention task**. Micro-behavioral indices of infant vigilance during the Cued Attention task were identified and calculated following guidelines specified in de Barbaro et al. (2011). Prior to coding infants' looking behavior, coders first identified and annotated the onsets and offsets of each trial (marked by the onset and offset of the target video sound) using the audio visualizations available in ELAN. Coders then coded each trial frame-by-frame at 30 frames per second, indexing infants' individual fixations and shifts of gaze to different areas in the room. As per de Barbaro et al. (2011), we counted infant looking behaviors as "fine-grained fixations" if the infant maintained her or his gaze for at least 230 milliseconds on the same area; however, we also included shorter looks within our proportional analyses of total looking time. Additionally, because the videos playing on the target monitors included moving animations that the infants could be visually tracking, we did not attempt to identify fine-grained fixations while infants were attending to the target videos (as was also the practice of de Barbaro et al. 2011), and target looking time was not included in subsequent fixation calculations.

Possible areas of infant focus during the Cued Attention task included *Target Monitor* (the monitor playing the video clip; as noted above, this monitor changed in each trial); *Non-Target Monitors* (any of the monitors *not* playing the video clip in a given trial); *Experimenter's Head/Torso* (the face/body of the experimenter directing the infant's attention in the task);

*Experimenter's Arm/Hand Extended* (indexed if the infant fixated on the experimenter's arm or hand while the experimenter was pointing to the target); *Down/other* (areas including the floor, the ceiling, and the infant's own body/feet); and *uncodable* (including moments in which the infant was blinking or had her/his eyes closed; these moments were excluded when assessing looking proportions). Based on the fine-grained fixations and gaze shifts identified, the following vigilance variables were calculated:

- *Latency to reorient*: This was calculated by identifying the first frame in each trial in which the infant began shifting (via head turn and/or saccade) in the direction of the target monitor for that trial (note that the infant did not actually have to make it to the target for the reorientation to count). The start time of the trial was then subtracted from the time corresponding to this frame, producing a latency for each trial. For our composite vigilance index (vigilance across all six trials), we used de Barbaro et al.'s (2011) measure of median latency to encompass infant vigilance, and reverse-coded this measure so that shorter latencies would indicate higher vigilance.
- *Target Hits:* This was the number of trials (across all six) in which the infant fixated on the target monitor at any point during the trial. A greater number of "hit" trials was hypothesized to indicate higher vigilance.
- *Mean Fixation Duration:* This variable was calculated by averaging the durations of all fine-grained fixations (not including target looking) observed across trials. As with reorientation latencies, this variable was also reverse-coded so that shorter durations would indicate higher vigilance.

- *Mean Fixation Rate (Fixations per second):* This was the number of fine-grained fixations observed, divided by the total duration of time spent looking at all areas other than the target monitor. (For analysis, higher fixation rates= higher vigilance)

All Cued Attention task videos were initially coded by the first author (a separate research assistant assigned a randomized number to each participant to help ensure blind review), and reliability was obtained via a second coder blind both to infants' experimental conditions and to the hypotheses of the broader study. The second coder coded 50% (3 trials) out of every video, which allowed for a sample from which to calculate the vigilance variables. Absolute intraclass correlation coefficients (ICC; single-measures) ranged from strong to excellent for each variable, and were similar to reliability levels reported in de Barbaro et al. (2011): .93 for median latency to reorient, .87 for Target Hits, .85 for mean fixation duration, and .76 for mean fixation rate.

**Experimenter-infant and caregiver-infant interactions**. Two sets of variables were coded for both the experimenter-infant interaction and the baseline caregiver-infant interaction. One set pertained to the experimenter's (or caregiver's) responses and actions, while the other encompassed infants' looking and vocalizations. Methods for coding each set of variables closely followed microbehavioral coding definitions described in Mason et al. (2018), and are briefly reiterated in the subheadings below. For the experimenter-infant interaction, coders identifying the experimenter's responses and infants' vocalizations (n=80) coded the entirety (10 minutes) of the interaction, while coders assessing infant looking (n=40) coded minutes 1-2, 5-6 and 9-10 only. These minutes were chosen as a means of evaluating infants' looking behaviors evenly across the session, while also compensating for the highly meticulous and laborious nature of frame-by-frame eyegaze coding. Similarly, coders evaluating infants' vocalizations during the baseline sessions (n=80) coded all ten minutes, while coders identifying caregivers' behaviors (n=80) and infant baseline eyegaze (n=20) coded 3-6 minutes. Analyses in our lab suggested that 3 minutes was adequate to evaluate the structure of caregivers' responses, as caregivers produced an average of 49.69 responses during the intervals coded (median=47, range 7-125 responses). However, given the difference in the amount of time coded between the experimenter interaction and baseline sessions, all variables compared between these sessions were normalized into proportional values (or rates per minute) rather than total numbers.

- *Experimenter and caregiver behaviors*. To identify experimenters' behaviors, coders first identified the onsets/offsets and modalities (verbal, behavioral or multimodal verbal/behavioral) of each experimenter action. Based on the spatial and/or verbal content of these responses, and infants' direction of gaze at the onset of each response, coders next identified whether the experimenter's response was *sensitive*, *redirective*, or *non-referential/unscripted*. Responses were labeled as *sensitive* if the experimenter's response engaged the object or area that the infant was currently visually focused on (for example, touching and/or verbally labeling the object that the infant was attending to, or acknowledging the infant dyadically if the infant was focused on the experimenter), and *redirective* if the experimenter attempted to shift the infant's gaze away from their current object of visual focus (exceptions: if the infant was gazing "into space", i.e., at the ceiling or wall, attempts to engage the infant were considered sensitive rather than redirective. Otherwise, actions attempting to interrupt infants' looks towards objects or the experimenter were redirective). *Non-referential/unscripted* responses occurred when experimenters provided vocal responses that were neither sensitive nor redirective (i.e., laughs, inspirations, narrative responses without references to infants' area of attention, non-sequiturs, vocal imitations, etc.); these did not happen often as they were "off-script" behaviors, but were identified to provide accurate insights into all behaviors that experimenters produced during the session.

Caregivers' behaviors were coded using the same definitions as above, though non-referential behaviors were not considered "unscripted". Two coders blind to the hypotheses of the study coded the experimenters' and caregivers' behaviors: one coded approximately half of the experimenter files, while the other coded the remaining experimenter and caregiver files as well as (for reliability) 30% of every file that the other coder annotated. Inter-rater reliability was analyzed using absolute intra-class correlation coefficients (single measures). Reliability was excellent for social partners' overall number of behaviors (ICC= .99), sensitive behaviors (ICC=.96), and redirective behaviors (ICC=.94), and strong with respect to social partners' number of non-referential (and/or "off-script") social behaviors (ICC=.85).

- *Infant behaviors*. Similar to Mason et al. (2018), infant looking was indexed frame-by-frame at 30 fps under one of the following categories: *objects* (including the toys, toybox, playmat, pillow, and chair; when experimenters or caregivers were manually engaged with objects, coders additionally annotated whether the objects that the infants were attending to were "experimenter/caregiver-engaged" or "unengaged"); *experimenter* (including the experimenter's face, upper body and hands); *caregiver* (the caregiver's face, upper body or hands); *other/undirected* (including the walls, floor, ceiling, and any other area not encompassed in the above categories), and *uncodable* (any moment in which the infants' eyes or locations of focus were out of view of the cameras). In addition to looking behaviors, one blind coder also identified the onsets and offsets of infants' prelinguistic vocal behaviors for both the experimental social interactions and infant-caregiver free play sessions. This was so that researchers could assess experimenters' and caregivers' specific levels of contingency to vocalizations, in addition to their overall response levels and contingency to infant looks.

For infant looking behaviors, 3 coders blind to experimental condition and the study hypotheses coded the experimental response sessions, and the first author coded 1 minute out of every interaction (after completing coding for the Cued Attention Task) to assess reliability. Because infant gaze categories also depended on experimenters' object handling, one of the coders coding experimenters' sensitive and redirective behaviors (above) additionally coded experimenters' overall object handling separately, while one of the 3 coders measuring infant gaze also coded a subset of experimenters' object handling for reliability. Absolute ICCs for infant attention variables (including total looking times and number of frame-by-frame shifts) ranged from .78-.99 for all coders, with most variables of interest reaching a level of .90 or higher (Supplemental Table S1). Additionally, reliability for social partners' object handling (absolute ICC, single-measures) was >.99.

After infants' and social partners' behaviors were coded, social partners' levels of overall responsiveness were analyzed by calculating their rate of responses per codable minute during the social interaction. Additionally, specific levels of experimenter contingency to infants' vocalizations (n=80) and looks (n=40) were also quantified, via in-house scripts developed in Python. These scripts matched infants' behaviors one-to-one with an experimenter response if the response occurred within a 2-second time window following the offset of an infant behavior. The 2-second contingency criterion was chosen based on previous studies in our laboratory and others (Goldstein & Schwade, 2008; Gros-Louis, West, Goldstein, & King, 2006; Mason et al., 2018; McGillion et al., 2013), which have found relations between infant learning and adults' contingent responding within this time window. Additionally, when evaluating experimenters' contingency to infants' looks, we used a criterion put forth in Yu & Smith (2016) to define "sustained looks" as $\geq$3sec. Though infant looks during the social interaction were also coded frame-by-frame to provide a more fine-grained analysis of infant looking for other analyses below (see *Experimenter Responsiveness and Infant Social Looking*), it was not anticipated that experimenters could achieve a level of coordination that would allow them to respond in time to infant fixations that were extremely short, given their lack of prior social experience with each infant. Thus, the 3-second gaze criterion is more temporally conservative than those of prior reports in which experimenters' social responding is manipulated (e.g. Miller et al., 2009), though perhaps less so than reports evaluating caregivers' moment-by-moment responding (e.g. Mason et al., 2018).

*Analyses*

Our main analyses had two primary aims: 1) to replicate prior work from de Barbaro et al. (2011) suggesting that infant looking behavior can be partly explained by biological models of arousal and vigilance elucidated in the neuroscience literature, and 2) to determine how social partners' relative levels of sensitivity, redirectiveness, and overall responsiveness (contingency) may influence infant arousal and consequent attentional organization.

For aim 1), we analyzed correlations between the arousal-based looking measures (latency to reorient, target hits, duration of fixations, rate of fixations) quantified from the Cued Attention Task. Following these analyses, we created a standardized vigilance composite index (as per de Barbaro et al. 2011) to evaluate how infants' overall arousal (using level of vigilance as an indirect measure of arousal) related to other looking measures in the Cued Attention task, including total looking time to salient stimuli as well as maintenance of salience-seeking across trials.

Regarding aim 2), we ran ANOVA analyses assessing the effects of experimental social contingency and content group assignments on infants' vigilance in the Cued Attention task. One ANOVA assessed the effects of group assignment on infants' overall vigilance composite across the entire Cued Attention task, while a second assessed the influence of group assignment on infants' trial-by-trial vigilance (more details in *Results* below). Significant effects were followed up with appropriate tests and ANCOVAs assessing the influence of more continuous measures of experimenters' social behavior (as well as background levels of caregiver responsiveness) on infant vigilance.

Secondary to the above aims, we also wished to evaluate whether differences in experimenters' contingency and content interacted to produce moment-by-moment changes in infants' social attention, and whether such changes might relate to differences in arousal as measured by infants' subsequent looking behavior on the Cued Attention task. To accomplish this, we compared infants' social looking and rates of gaze shifting (described in *Coding* above) across experimenter response groups, using appropriate ANOVA analyses. We then ran correlations evaluating relations between these measures and infants' composite vigilance indices on the Cued Attention Task. All analyses were completed in SPSS, while data preparation was completed in R and Python (scripts and syntax available on request).

# Results

## *Replication of de Barbaro et al. (2011)*

Table 2.1 depicts descriptive statistics for the behavioral indices of infant arousal (i.e., the vigilance measures) captured within the Cued Attention task. Individual variation comparable to that reported in de Barbaro et al. (2011) was observed, suggesting that the relations between these variables could be further examined. To assess these relations, we calculated Pearson correlations between each individual behavioral measure (note that infants' reorientation latencies and fixation durations were reverse-coded, so that higher scores would imply higher vigilance[5]). These correlations are presented in Table 2.2. As predicted by the LC-NE model, all correlations were significant and positive (all ps<.05).

To further replicate de Barbaro et al.'s (2011) findings, we next created a composite vigilance index by z-standardizing and averaging the four individual arousal indices. Using this vigilance composite, we examined whether higher vigilance would correspond to a higher

TABLE 2.1.
Descriptive Statistics for Infant Behavioral Indices of Arousal in the Cued Attention Task

| **Descriptive Statistics** | *Latency to Reorient (sec)* | *Target Hits* | *Mean Fixation Duration (sec)* | *Mean Fix. Rate (fixations/sec)* |
|---|---|---|---|---|
| *Average* | 0.62 | 5.45 | 0.80 | 1.25 |
| *(SD)* | (0.31) | (0.63) | (0.22) | (0.29) |
| *Range* | 0.10-2.42 | 4-6 | 0.45-1.53 | 0.64-1.94 |

[5]As per de Barbaro et al. (2011), we reverse-coded the latency and duration measures so that shorter latencies (and shorter fixation durations) would equate to higher vigilance. However, the original latency and duration values also significantly correlated with the other behavioral arousal measures (Target "Hits" and average non-target fixation rate) listed in Table 2. Additionally, to replicate de Barbaro et al. (2011) as closely as possible, we used infants' median latencies to calculate correlational comparisons and vigilance composites rather than mean latencies, as some (but not all) infants exhibited one trial in which their latencies deviated considerably from their reorientation latencies in every other trial.

TABLE 2.2.
Pearson's Correlations between Individual Behavioral Indices of Arousal in the Cued Attention Task

| ***Measure*** | ***1*** | ***2*** | ***3*** | ***4*** | ***5*** |
|---|---|---|---|---|---|
| 1. Median latency to reorient (reverse-coded) | --- | .28* | .36** | .35** | .61** |
| 2. Target hits | | --- | .69** | .64** | .81** |
| 3. Mean fixation duration (reverse-coded) | | | --- | .95** | .92** |
| 4. Mean fixation rate | | | | --- | .91** |
| *5. Summary vigilance composite* (average of all z-standardized scores for measures 1-4…) | | | | | --- |

*p<.05; **p<.01

proportion of time looking at the most salient visual stimuli available during the Cued Attention task—specifically, the audiovisual animations playing on the target monitors in each trial. As expected, infants' overall vigilance was strongly positively correlated with infants' proportion of target monitor looking across trials ($r$=.56, p<.001). Infant vigilance was also negatively correlated with % time spent attending to the experimenter during the Cued Attention Task ($r$= -.44, p<.001), though vigilance was uncorrelated with the number of trials in which infants looked to the experimenter's gaze-and-point cues (p=.67). Additionally, infant vigilance was not significantly correlated with time spent looking down or to non-target monitors (both ps>.10).

Finally, we also wanted to re-examine de Barbaro et al.'s (2011) finding that infants low in vigilance had greater fluctuations in attention to salient stimuli (the target monitors) compared to high-vigilance infants as the Cued Attention trials progressed. To evaluate this finding, we followed de Barbaro et al.'s method of conducting a median-split analysis of "high" and "low" vigilance infants[6] from our 80 usable participants. For each infant, an absolute difference score

[6] Though order of monitor and video presentation in the Cued Attention task was evenly counterbalanced across infants in our different social interaction groups, conducting a median-split analysis of "high" and "low" vigilance

was calculated between their summed proportion of target looking time in trials 1 and 2, and their summed proportion of target looking time in trials 5 and 6. A larger difference in proportional looking time between the first and last sets of trials would indicate greater flexibility in attention, which we theorized would be characteristic of less vigilant infants. After calculating these difference scores, we compared the average magnitude of difference in target looking between "high vigilance" and "low vigilance" groups. Overall, "low vigilance" infants showed a greater magnitude of difference in target looking between trials 1-2 and 5-6 (mean absolute difference= 41.94% of total looking time, SD= 33.76%) than did "high vigilance" infants (mean absolute difference= 23.56% of total looking time, SD= 18.20%). The magnitude of change between groups was significant, $t(59.91^{7}) = 3.03$, $p=.004$). Intriguingly, a plot of infants' target looking across trials (Figure 2.2) indicates that while "high-vigilance" infants maintained high target looking consistently during trials, "low-vigilance" infants actually started relatively unengaged in the targets, but increased their target looking in trials 5 and 6, such that their levels of engagement were approximately equal to that of "high-vigilance" infants by the end of the task. Together, these results suggest that low-vigilance infants showed significantly greater fluctuations in attention to the salient target stimuli, despite the relative equality of informational content contained in each new target.

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infants means that unless infants' post-interaction vigilance is equal across social interaction groups (we hypothesized that this would not be the case), then it is possible that "high" and "low" vigilance infants may have different monitor/clip order presentations. To ensure that "high" and "low" vigilance infants did not have different monitor or clip presentation orders, we ran chi-squared analyses assessing whether there were significant differences between median-split groups in monitor order or video clip order. Median-split groups were approximately evenly matched on monitor order ($\chi^2(5,80)=3.83$, $p=.62$(n.s.)), and were (by chance) exactly matched on clip order ($\chi^2(1,80)=0.00$, $p=1.00$ (n.s.)), suggesting that order of monitor/clip presentation would not present a confound in this analysis.

[7] Because Levene's test was violated, Welch's corrected t statistic was used

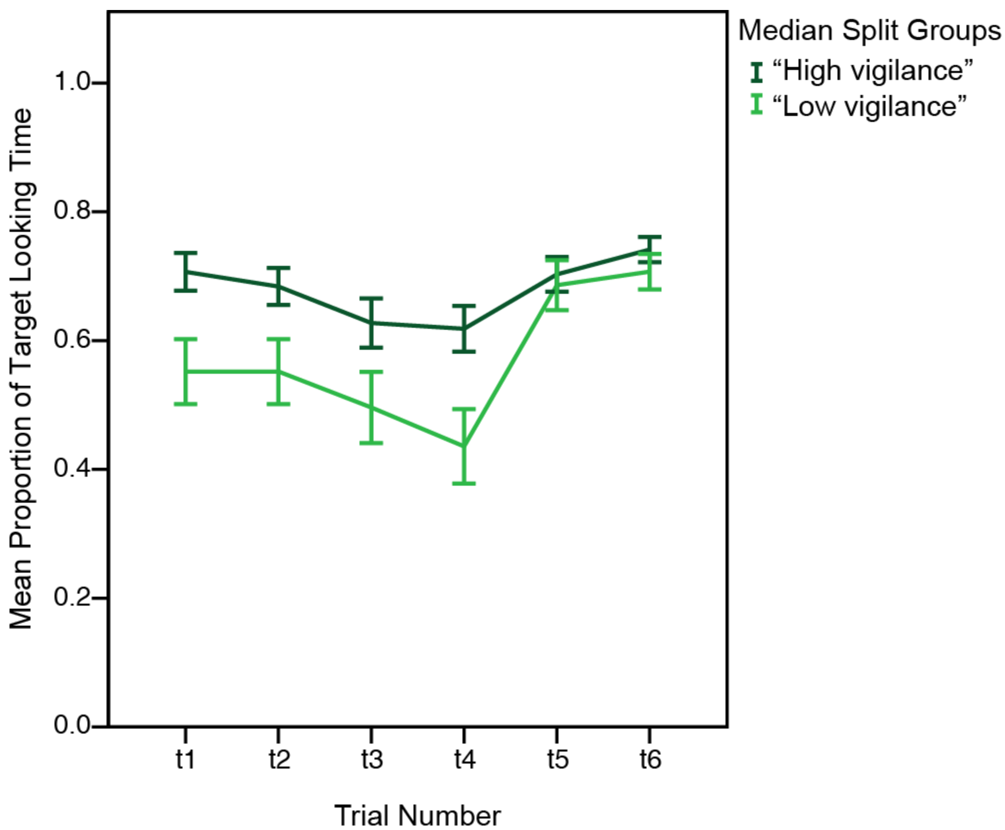


*Figure 2.2*. "High vigilance" and "low vigilance" infants' proportions of looking time at salient target videos across trials of the Cued Attention task. Infants identified as "high vigilance" (via median-split analysis) exhibited a fairly consistent and high degree of target looking across trials, whereas infants identified as "low vigilance" showed greater fluctuations in attending, with less relative time spent looking in early and middle trials.

*Experimentally-controlled social influences on infant vigilance*

**Experimenter response characteristics**. Following our analysis and replication of the arousal measures derived from de Barbaro et al.'s (2011) Cued Attention task, our next aim was to determine whether experimentally-controlled differences in adults' timing and content of social feedback to infants predicted differences in infants' subsequent vigilance (as measured by the Cued Attention task). First, to test the effectiveness of our response schedules on creating distinctive differences in experimenters' contingency and content (sensitivity/redirectiveness), we compared experimenters' average response characteristics across *HCHS*, *HCHR*, *LCHS*, and *LCHR* response groups (Figures 2.3a-d). As expected, when following High Contingency response schedules (*HC*HS and *HC*HR), experimenters provided more responses throughout the interaction than when following Low Contingency response schedules *(LC*HS and *LC*HR; Fig. 2.3a). Additionally, when following the *HCHS* and *HCHR* response schedules, experimenters responded to a higher proportion of infants' vocalizations than when following either of the low contingency response schedules (*LCHS* and *LCHR*; Fig. 2.3c). To assess whether these differences in rate and timing of responses were significant, we ran two one-way ANOVAs evaluating the effect of response group (*HCHS, HCHR*, *LCHS*, and *LCHR*) on 1) experimenters' overall number of responses (Figure 2.3a), and 2) the proportion of infants' vocalizations for which experimenters provided a response (Figure 2.3c). Both ANOVAs were significant (overall number of responses: $F(3,74)= 71.43$, $p<.001$; proportion of infant vocalizations that received a response: $F(3,74)= 16.57$, $p<.001$). Post-hoc comparisons of experimenters' number of responses (using Bonferroni-adjusted p-values, as provided by the POSTHOC function in SPSS[8]) revealed significant differences between the high contingency and low contingency groups (*HCHS* vs. *LCHS*: mean difference= 65.79 responses, $p<.001$; *HCHS* vs. *LCHR*: mean difference= 66.86 responses, $p<.001$; *HCHR* vs. *LCHS*: mean difference= 56.93 responses, $p<.001$; *HCHR* vs. *LCHR*: mean difference= 58.00 responses, $p<.001$), and no significant differences between groups falling under the same contingency schedules (*HCHS* vs. *HCHR*: mean difference= 8.86 responses, $p=.87$; *LCHS* vs. *LCHR*: mean difference= 1.07 responses, $p>.99$). Post-hoc tests evaluating experimenters' contingency to vocalizations between groups produced the same

[8] For Bonferroni adjustment, rather than comparing the original p-values to a Bonferroni threshold, the /POSTHOC=BONFERRONI ALPHA(0.05) function multiplies the original p-values by the number of comparisons, creating adjusted p-values that can then be compared to the original alpha level of p<.05. More information on the algorithm is available here: : https://www-01.ibm.com/support/docview.wss?uid=swg21476685

pattern of findings, with significant differences observed between high contingency and low contingency groups (*HCHS* vs. *LCHS*: mean difference= 22.06% of infant vocalizations, p<.001; *HCHS* vs. *LCHR*: mean difference= 21.64% of infant vocalizations, p<.001; *HCHR* vs. *LCHS*:

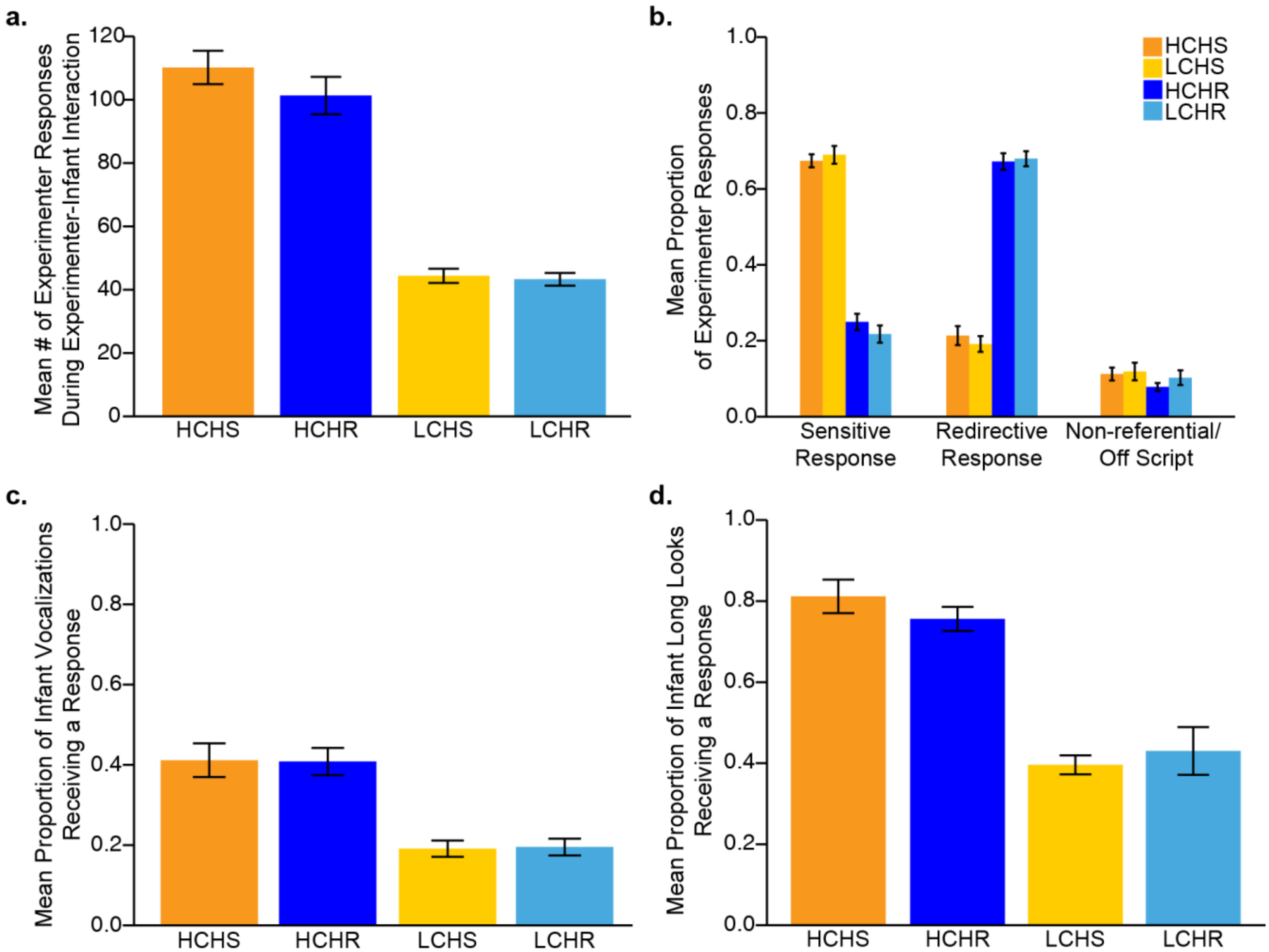


*Figure 2.3.* Response characteristics of experimenters following dissimilar social response schedules. HCHS= high contingency, high sensitivity; HCHR= high contingency, high redirectiveness; LCHS= low contingency, high sensitivity; LCHR= low contingency, high redirectiveness. Experimenters exhibited distinct rates and levels of overall responding when following different contingency schedules (high vs. low contingency), and different content of responding when following differing content schedules (high sensitive vs. high redirective)

mean difference= 21.72% of infant vocalizations, $p<.001$; *HCHR* vs. *LCHR*: mean difference= 21.30% of vocalizations, $p<.001$) while no differences were observed between groups falling under the same contingency schedules (*HCHS* vs. *HCHR*: mean difference= 00.33% of infant vocalizations, $p>.99$; *LCHS* vs. *LCHR*: mean difference= 00.42% of infant vocalizations, $p>.99$).

Among the subset of infants (n=40) for whom we identified infants' looking patterns during the experimental social interaction, we also evaluated experimenters' average contingency to infants' sustained looks (≥3 sec) across response groups (Figure 2.3d). To do so, we ran a one-way ANOVA assessing the effect of response group (*HCHS, HCHR, LCHS,* and *LCHR*) on the proportion of infants' sustained looks that received an experimenter response. The ANOVA was significant ($F(3,36)= 28.21$, $p<.001$), and Bonferroni-corrected post-hoc comparisons revealed that the differences were again present between the high and low contingency groups (*HCHS* vs. *LCHS*: mean difference= 41.60% of infant sustained looks, $p<.001$; *HCHS* vs. *LCHR*: mean difference= 38.16% of infant sustained looks, $p<.001$; *HCHR* vs. *LCHS*: mean difference= 36.05% of infant sustained looks, $p<.001$; *HCHR* vs. *LCHR*: mean difference= 32.61% of sustained looks, $p<.001$). Also as anticipated, there were no differences in infant look responding between groups assigned to the same contingency level (*HCHS* vs. *HCHR*: mean difference= 5.55% of sustained looks, $p>.99$; *LCHS* vs. *LCHR*: mean difference= 3.44% of sustained looks, $p>.99$). Together, these analyses indicate that our contingency manipulation was effective in creating distinct patterns of "high" and "low" contingency regardless of experimenters' Content schedule (*HS* vs. *HR*), meaning that the effect of Contingency (*HC* and *LC*) could be studied independent of content in subsequent analyses.

The *content* of experimenters' responses between groups is shown in Figure 2.3b. Overall, experimenters appeared to provide more sensitive responses on average when following

High Sensitive content schedules (HC*HS* and LC*HS*) than when following High Redirective (HC*HR* and LC*HR*) schedules (Fig. 2.3b, first grouped column). In comparison, experimenters seemed to provide more redirective responses when following High Redirective schedules (*HCHR* and *LCHR*) than when following High Sensitive (*HCHS* and *LCHS*) schedules (Fig. 2.3b, second grouped column). To explore whether these group differences were significant, and whether experimenters following either High Sensitive or High Redirective content schedules provided significantly more of their assigned response type compared to their unassigned response type, we ran a 4 (Response Schedule (Group): *HCHS, HCHR, LCHS,* and *LCHR*) x 2 (response type: sensitive vs. redirective) ANOVA on the proportion of responses of each type that experimenters provided. There was no main effect of group in the model, nor was there a main effect of response type; however, there was a highly significant group x response type interaction ($F(3,76)= 182.86$, $p<.001$). Tests of simple effects revealed that both High Sensitive groups provided significantly more sensitive than redirective responses during their social interactions with infants (*HCHS*: $F(1,19)= 135.95$, $p<.001$; *LCHS*: $F(1,19)= 175.98$, $p<.001$), and that both High Redirective groups provided significantly more redirective than sensitive responses during their social interactions (*HCHR*: $F(1,19)= 100.07$, $p<.001$; *LCHR*: $F(1,19)= 147.21$, $p<.001$). Additionally, when comparing levels of sensitive responding between groups, both High Sensitive groups provided significantly more sensitive responses when compared to either of the High Redirective groups (main $F(3,79)= 146.92$, $p<.001$; *HCHS* vs. *HCHR* mean difference= 42.46% of total responses, $p<.001$; *LCHS* vs. *HCHR* mean difference= 44.02%, $p<.001$; *HCHS* vs. *LCHR* mean difference= 45.65%, $p<.001$; *LCHS* vs. *LCHR* mean difference= 47.22%, $p<.001$), and there were no differences between levels of sensitive responding between groups falling under the same Content schedules (*HCHS* vs. *LCHS* mean difference= 1.56% of all responses, p>.99; *HCHR* vs. *LCHR* mean difference= 3.19% of all responses, p>.99). Likewise, both High Redirective groups provided significantly more redirective responses when compared to either High Sensitive Group (main *F*(3,79)= 154.98, p<.001; *HCHR* vs. *HCHS* mean difference= 45.86% of responses, p<.001; *HCHR* vs. *LCHS* mean difference= 48.08% of responses, p<.001; *LCHR* vs. *HCHS* mean difference= 46.61%, p<.001; *LCHR* vs. *LCHS* mean difference= 48.83%, p<.001), with no significant differences observed between groups with the same Content schedules (*HCHR* vs. *LCHR* mean difference= 00.75% of responses, p>.99; *HCHS* vs. *LCHS* mean difference= 2.22% of responses, p>.99). These results indicate that our Content manipulation was successful in creating different experimentally-controlled patterns sensitive and redirective responding across levels of Contingency (HC vs. LC), meaning that the effect of Content could be evaluated independent of Contingency in analyses to follow.

**Do differences in experimenters' contingency and content predict infant vigilance on the Cued Attention task**? With our experimental manipulation thus validated, we next examined whether experimenters' contingency and content during their social interactions with infants related to differences in infants' later vigilance in the Cued Attention task. As a first step in exploring this question, we ran a 2 (Contingency Schedule: *HC* vs. *LC*) x 2 (Content Schedule: *HS* vs. *HR*) ANOVA assessing the effects of contingency and content on infants' standardized vigilance composite index score, as calculated in de Barbaro et al. (2011) (see *Replication* above). We found a marginal main effect of Contingency Schedule (*F*(1,76)= 3.12, p=.08), with infants in the High Contingency groups having lower overall vigilance scores than infants in the Low Contingency groups (mean *HC(HS and HR collapsed)*= -.16, SD=.82; mean *LC(HS and HR* *collapsed)*= .16, SD=.78). There was no main effect of Content Schedule (p=.41), and no Contingency x Content interaction (p=.39).

As we were also interested in infants' trajectory of vigilance behaviors across each trial of the Cued Attention task, we next created summary vigilance indices for each individual trial by calculating, z-standardizing and averaging infants' fixation rates per trial, infants' reverse-coded latency to reorient for each trial, and infants' reverse-coded trial-by-trial fixation durations (note that because "Target Hits" becomes a binary variable when assessed per trial, this variable was excluded in infants' trial-by-trial calculations). The average trial-by-trial vigilance indices of infants assigned to different Contingency and Content groups are displayed in Figures 2.4a-c. To evaluate the effects of experimenters' contingency and content on infants' trial-by-trial vigilance, we ran an autoregressive (AR(1)) mixed-model ANOVA[9] including Contingency group (*HC* vs. *LC*) and Content group (*HS* vs. *HR*) as fixed effects; Trial Number (trials 1-6) as a repeated and fixed effect; and Subject Number as a random effect (used for grouping, but not analyzed for significance). When adding trial number to the model, the main effect of contingency group became significant ($F$(1,171.33)= 3.98, p=.048). However, there was no significant contingency group x trial number interaction (p=.66). Additionally, there were no main effects of content group (p=.22) or trial number (p>.99); no content group x trial number interaction (p=.66); no contingency group x content group interaction (p=.36); and, no contingency group x content group x trial number interaction (p=.66). As shown in Figure 2.4a, infants in the high contingency groups appeared to exhibit somewhat less vigilance than infants in the low contingency groups across most trials, though this effect appeared especially pronounced during the second half (i.e. trial 4) of the task.

[9] As we expected trials closer in time to be more correlated than trials further in time, an AR(1) covariance structure was recommended for this analysis.

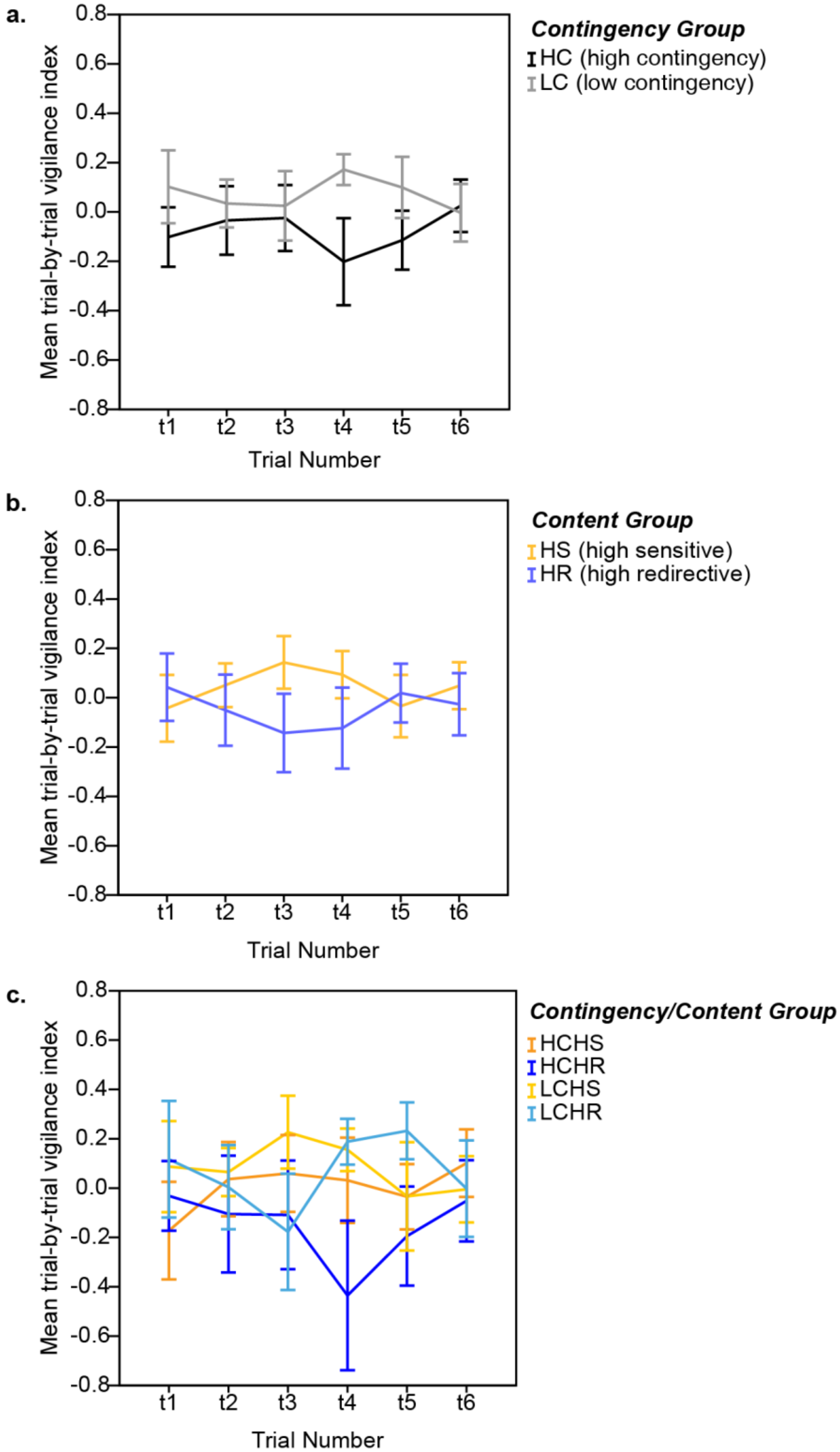


*Figure 2.4.* Infants' trial-by-trial vigilance indices, averaged across levels of a) Contingency condition; b) Content condition; and, c) All possible crossings of contingency and content conditions. Overall, experimenters' level of contingency was most predictive of infants' subsequent vigilance, though there is a high degree of variability in infants' vigilance overall across trials and groups.

**Possible mediating effects of caregiver response characteristics on infant vigilance**. Given the high variability in infants' Cued Attention task vigilance scores within different experimenter response schedules, we next explored whether aspects of infants' history of social experience with caregivers might be mediating the effects of experimenters' social responses on infant vigilance. First, we ran correlations between caregiver response characteristics and infants' summary vigilance composite. Characteristics tested included caregivers' proportions of sensitive and redirective responding; caregivers' average rates of responding per minute; caregivers' levels of contingency to infants' vocalizations; and, the absolute difference scores between each of these variables and confederates' levels of the equivalent behavior during the experimental social interaction. No correlations were significant (all $ps > .20$), suggesting that infants' social backgrounds were not directly predictive of vigilance in the Cued Attention task.

Next, we explored whether controlling for the absolute magnitude of difference in overall responding between caregivers and experimenters would influence the predictive power of experimenters' contingency and content schedules on infants' summary vigilance composite. To quantify caregivers' and experimenters' absolute magnitude of difference in responding, we first calculated caregivers' and experimenters' average rates of responding per minute, then took the absolute value of the difference between these rates (with larger values equating to a larger magnitude of difference between caregivers' and experimenters' levels of responding). We then included this variable as a covariate in our original 2 x 2 ANOVA analysis, including Contingency schedule (*HC* vs. *LC*) and Content schedule (*HS* vs. *HR*) on infants' summary vigilance composite. The marginal main effect of contingency schedule became slightly stronger ($F(1,72) = 3.94$, $p = .051$); however, there was still no main effect of content schedule ($p = .47$), and no contingency x content interaction ($p=.55$). Additionally, there was no significant main effect of the covariate on predicting infants' vigilance ($p=.29$).

*Experimenter responsiveness and infants' social looking*

As a final exploration of the effects of experimenters' contingency and content on infants' attention, we decided to evaluate infants' moment-by-moment looking during the experimental social interaction itself, and whether systematic differences in infant looking occurred under different experimenter response conditions. Using our subset of infants for whom data was collected on eyegaze during the social interaction ($n=40$, 10 per experimenter response schedule), we first quantified infants' distribution of gaze to different areas as they interacted with their social partners (Figures 2.5a-b). When experimenters were not engaged with objects, infants in all groups preferred attending to objects more than any other area (Figure 2.5a), which is typical for infants of this age range in naturalistic environments (e.g. Deák, Krasno, Triesch, Lewis, & Sepeta, 2014). To assess whether this looking preference was significant compared to their looking at their next highest looking category (experimenters; Fig. 2.5a), we ran a 4 (Response schedule (Group): *HCHS, HCHR, LCHS,* and *LCHR*) x 2 (Looking Area: objects vs. experimenters) mixed repeated-measures ANOVA on infants' proportions of total looking time. There was a significant main effect of Looking Area ($F(1,36)= 82.03$, $p<.001$), with no main effect of group ($p=.58$), and no significant looking area x group interaction ($p=.90$).

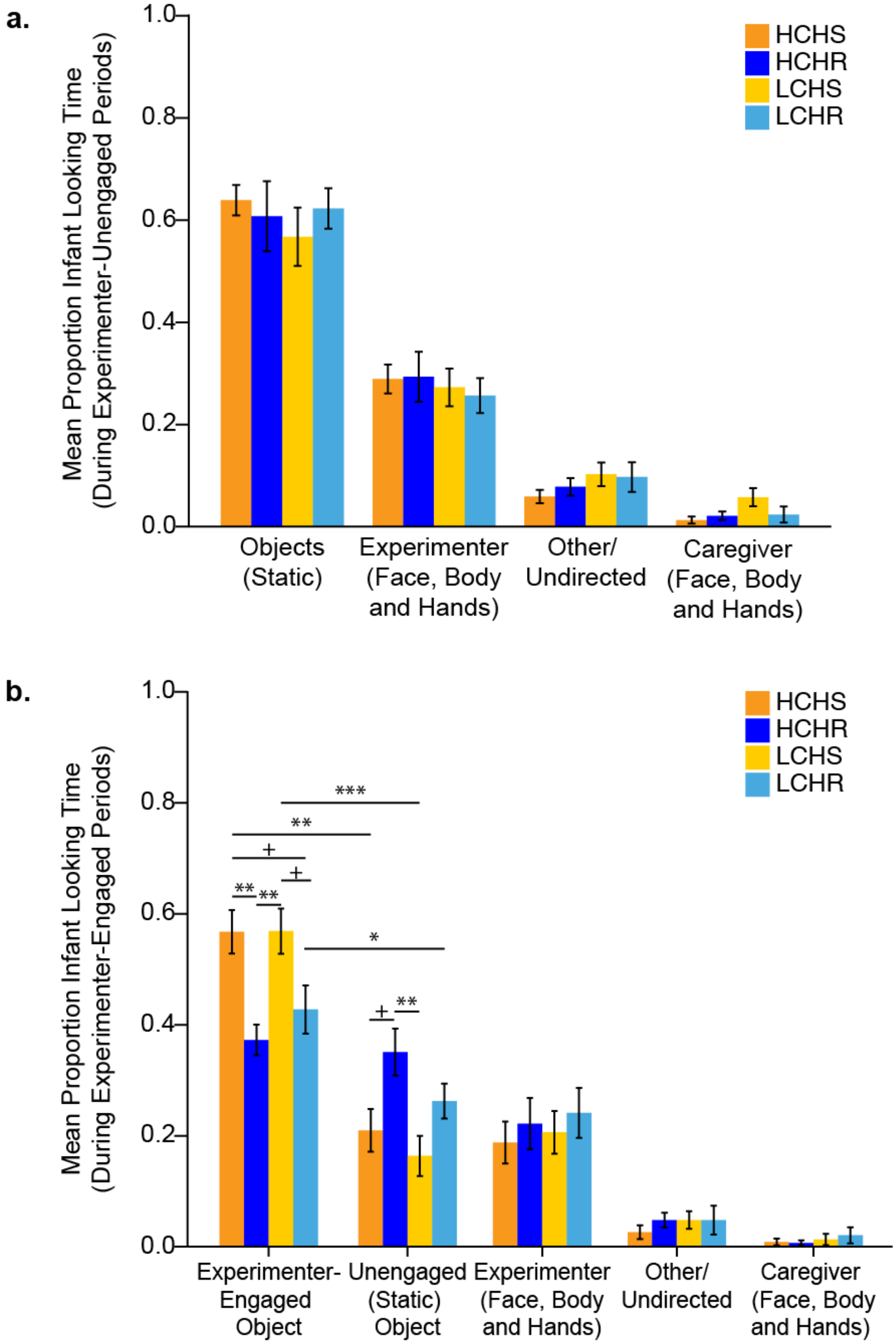


*Figure 2.5*. Preliminary analyses (n=40) of infants' distributions of looking across their social interaction with an unfamiliar experimenter. a) Depicts infants' relative proportions of looking at various areas of interest when experimenters are not manually engaged with objects in the room, while b) illustrates infant looking during moments in which experimenters are touching or holding at least one object. Dark orange indicates averages for infants exposed to highly

contingent/highly sensitive social partners; dark blue shows averages for infants exposed to highly contingent/highly redirective social partners; light orange portrays averages for infants exposed to low contingency/highly sensitive social partners; and, light blue depicts averages for infants exposed to low contingency/highly redirective social partners. +p<.10 (after Bonferroni correction); *p<.05 (“); **p<.01 (“); ***p<.001 (“).

When experimenters were engaged with objects, infants across response groups showed some variability in their looking preferences, though all groups spent the majority of their time either looking at the experimenter's engaged objects, or at unengaged objects (Fig. 2.5b). As social partners' engaged objects have typically been shown in previous work to be the most salient and preferred areas of focus for infants during naturalistic interactions (Deák et al., 2014), we were curious as to whether the differences in looking preferences for engaged vs. unengaged objects between and within response groups were significant. To answer this question, we ran a 4 (Response Schedule (Group): *HCHS, HCHR, LCHS,* and *LCHR*) x 2 (Looking Area: experimenter engaged vs. unengaged objects) mixed repeated-measures ANOVA on infants' proportions of looking time. There was a significant main effect of Looking Area ($F(1,36)= 56.67$, $p<.001$), with no main effect of group ($p=.53$). However, there was a significant looking area x group interaction ($F(3,36)= 7.92$, $p<.001$). Tests of simple main effects showed that while infants in the *HCHS*, *LCHS* and *LCHR* response groups showed significant looking preferences for experimenter-engaged objects over unengaged objects (*HCHS:* $F(1,9)= 27.95$, $p=.001$; *LCHS*: $F(1,9)=37.24$, $p<.001$; *LCHR:* $F(1,9)=7.75$, $p=.021$), infants in the *HCHR* response group did not show a looking preference for engaged objects over unengaged objects ($F(1,9)=.14$, $p=.72$). Additionally, there was a significant effect of group on infants' proportion of looking to engaged objects ($F(3,36)= 6.79$, $p=.001$), and a significant effect of group on infants' proportion of looking to unengaged objects ($F(3,36)= 4.64$, $p=.008$). Post-hoc tests with Bonferroni-corrected p-values indicated that infants in the *HCHS* and *LCHS* groups spent significantly more time looking at engaged objects than infants in the *HCHR* group (*HCHS* vs. *HCHR*: mean difference= 19.52% of total looking time, p=.006; *LCHS* vs. *HCHR*: mean difference= 19.63%, p=.005), and marginally more time looking at engaged objects than infants in the *LCHR* group following Bonferroni adjustment (*HCHS* vs. *LCHR*: mean difference= 14.03% of looking time, p=.082; *LCHS* vs. *LCHR*: mean difference= 14.13%, p=.078). In comparison, infants in the *HCHR* group spent significantly more time attending to unengaged objects than infants in the *LCHS* group (mean difference= 18.73% of looking time, p=.007), and marginally more time attending to unengaged objects than infants in the *HCHS* group after Bonferroni adjustment (mean difference= 14.13% of looking time, p=.067). No other pairwise comparisons approached significance (all *p*s>.41).

In addition to infants' distribution of looking preferences to areas of varying salience, we also analyzed infants' gaze shifting during their experimental social interactions as a potential measure of arousal in the social context. Infants' relative rates of gaze shifting across groups is illustrated in Figure 2.6. Infants across groups did not show any strong differences in their rates of shifting, though infants in the *HCHS* group appeared to shift gaze marginally more than infants in the other response groups. A one-way ANOVA assessing the effect of group (*HCHS, HCHR, LCHS,* and *LCHR*) on infants' gaze shifting was not significant ($F(3,36)= 1.60$, p=.21).

Finally, we ran a preliminary assessment of whether certain looking behaviors of interest during the social interaction (relative distributions of looking at more salient vs. less salient

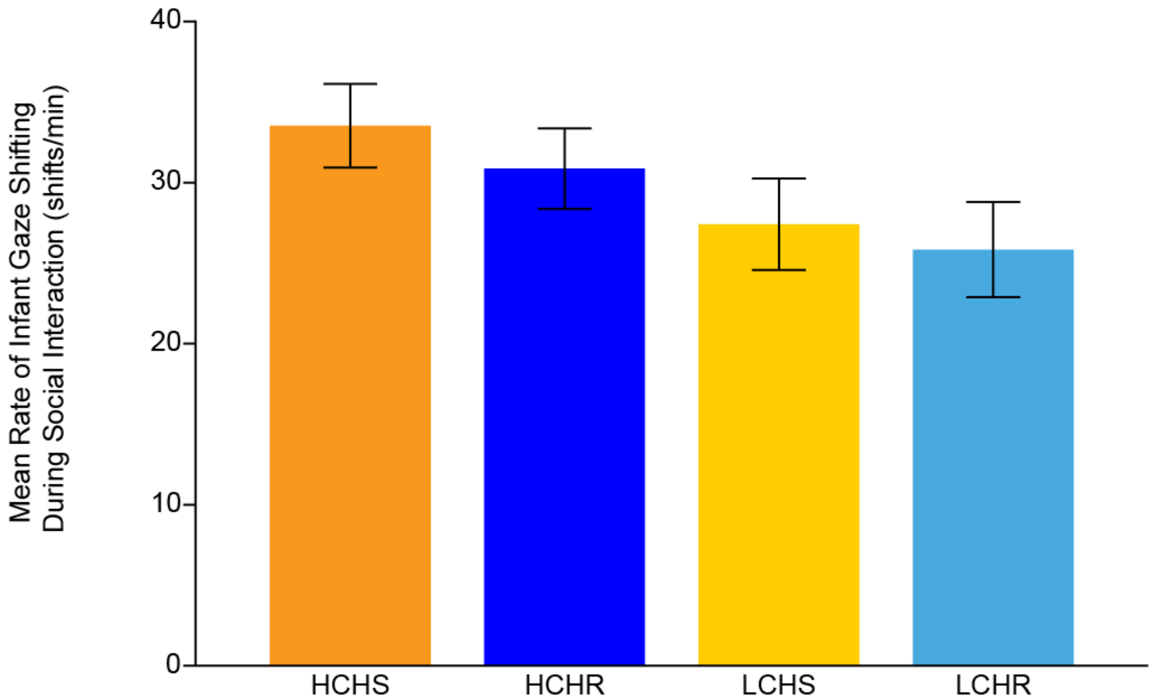


*Figure 2.6*. Preliminary analyses (n=40) of infants' average rates of gaze shifting during their social interaction with an unfamiliar experimenter. Dark orange= average for infants exposed to highly contingent, highly sensitive interaction partners; dark blue= average for infants exposed to highly contingent, highly redirective social partners; light orange= average for infants exposed to low contingency, highly sensitive social partners; and, light blue= average for infants exposed to low contingency, highly redirective social partners.

objects, and rate of fixations) corresponded to infants' vigilance differences in the Cued Attention Task. Because infant social looking data was only quantified for a subsample of our participants, we did not include these variables in a larger ANCOVA model assessing their relative contributions to infant vigilance in the context of experimenters' Contingency and Content groups, but rather analyzed basic correlations between these variables and infants' composite vigilance index in the Cued Attention task. Our preliminary correlations are shown in Table 2.3. Among the variables analyzed, infants' proportion of looking to *unengaged objects* during experimenter object-engaged periods was significantly negatively correlated with infants' vigilance composite scores on the Cued Attention task ($r$= -.36, p=0.024), meaning that infants

TABLE 2.3.
Pearson's Correlations between Infant Gaze Behaviors during the Experimental Social Interaction, and Summary Vigilance in the Cued Attention Task

| ***Measure*** | ***1*** | ***2*** | ***3*** | ***4*** |
|---|---|---|---|---|
| 1. % Looking at *experimenter-engaged objects* during engaged periods | --- | -.57** | .007 | -.038 |
| 2. % Looking at *unengaged objects* during engaged periods | | --- | -.046 | -.36* |
| 3. Rate of fixations/min during social interaction | | | --- | -.098 |
| 4. *Summary vigilance composite* during Cued Attention task | | | | --- |

*p<.05; **p<.01

who looked more to unengaged objects during the social interaction (in comparison to more salient engaged objects) showed less subsequent vigilance in the Cued Attention task (Figure 2.7). No other correlations between social gaze variables and the Cued Attention task were significant.

## Discussion

The results of our study provide further evidence in support of the view that infant looking patterns can be explained in part by neurobiological models of arousal regulation (Aston-Jones & Cohen, 2005; de Barbaro et al., 2011), and that differences in proximal social experiences may produce varying effects on early arousal and performance on subsequent attention-related tasks. Specifically, we replicated de Barbaro et al. (2011)'s findings that behavioral indices of arousal operationalized in the animal literature correlated significantly with one another in the context of infants' looking during an attention task, and that variation in these indices predicted dynamic fluctuations in infant attention to salient stimuli that are not predicted by strictly information-processing models. Using this same attention task, we also found that

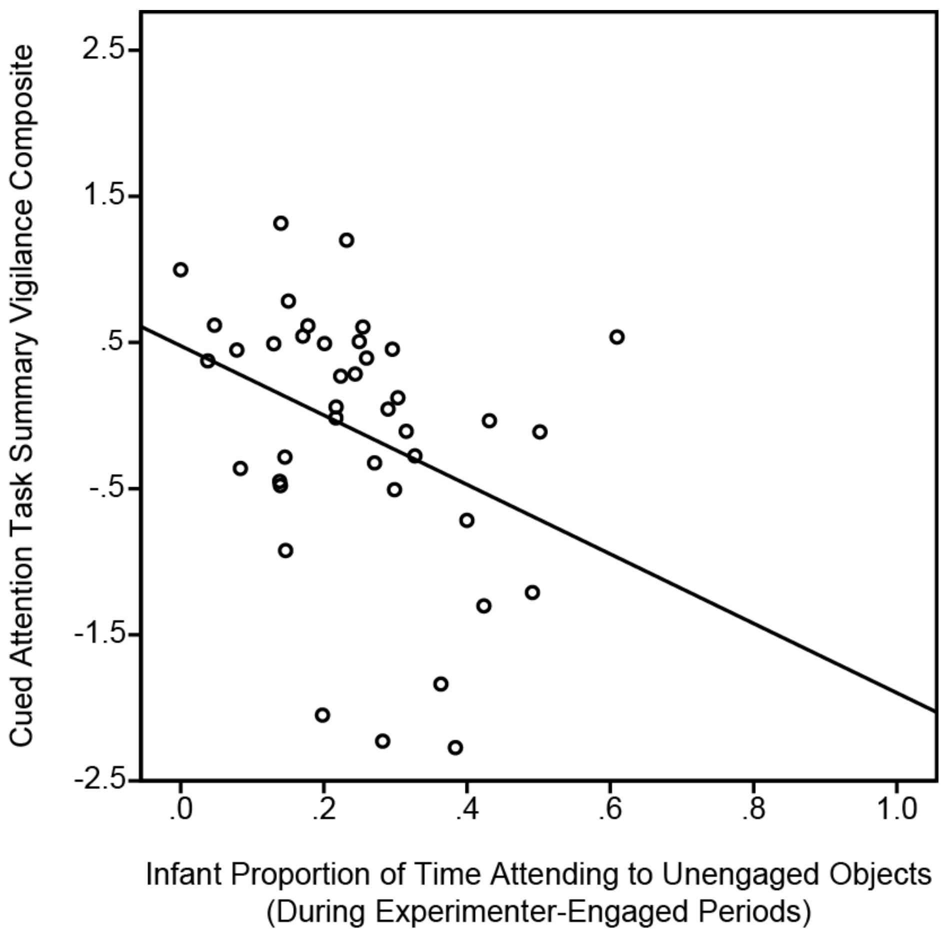


*Figure 2.7*. Preliminary analyses (n=40) of relations between infants' unengaged object looking during their social interaction with an unfamiliar experimenter, and infants' subsequent vigilance on the Cued Attention Task (indexed by their across-trials summary vigilance composite). The x-axis denotes infants' relative proportion of time spent looking at unengaged objects during moments in which experimenters were touching, holding and/or manipulating at least one object. The correlation observed was significant (r= -.36, p=0.024).

differences in social partners' overall levels of responding (contingency) during a prior social interaction corresponded to changes in infant vigilance (which presumably reflects changes in arousal) that were observable in the task. While the *content* of social partners' responses wasn't directly predictive of later vigilance changes, preliminary analyses suggested that contingency and content may interact to produce changes in infants' behavior during the social interaction, and that some of these changes in behavior (specifically, amount of looking to unengaged objects) may map on to subsequent vigilance differences.

In terms of our main findings, we observed that infants whose social partners responded frequently to their looks and vocalizations subsequently showed less trial-by-trial vigilance on the Cued Attention task than infants whose social partners were minimally responsive. While we had expected contingency and content to potentially interact in determining infants' later vigilance, the fact that there was no effect of experimenters' content on infant vigilance suggests perhaps that overall responsiveness may be a strong signal of predictability, even in the context of differences in response content. For example, it may be the case that infants whose social partners responded frequently to their behavior were able to learn more quickly the structure of their social partners' responses, including whether their social partners' responses were more frequently sensitive or redirective (i.e., their response content). With such information, infants in the High Contingency groups may have been able to reduce uncertainty regarding the relative "value" of their experimenters' responses, and thus potentially reduce arousal associated with unpredictability (Miller, 1982). This notion is tentatively supported by our preliminary finding that infants exposed to *HCHR* (high contingency and high redirectiveness) experimenters showed no significant looking preferences for their experimenters' objects during the social interaction, as it indicates that these infants may have learned more readily that their experimenters were likely to be engaged with objects that they themselves were not already interested in. In contrast, infants exposed to *LCHR* (low contingency and high redirectiveness) experimenters maintained a significant looking preference for their experimenters' held objects during the social interaction, which may indicate (though other interpretations are possible) that they did not learn as readily that their experimenters' engaged objects would not often be aligned with what they were interested in. Alongside the possibility that less consistent responding would create greater challenges in infants' ability to learn the general content characteristics of their experimenters' responses, less responding also may have prevented infants from being able to easily build an association between their own behaviors and the responses of the experimenter, thus contributing to greater uncertainty regarding when (and under what circumstances) their experimenter would respond to them. Such increases in relative uncertainty and unpredictability on a broad scale may have had more salient effects than any unpredictability induced by the content (i.e. redirectiveness vs. sensitivity) of experimenters' responses, though from an information-seeking perspective, it is unclear whether the uncertainty induced by the low contingency conditions was overwhelming (i.e., unlearnable for the infants) or "just complex enough" to encourage optimal attentional engagement and learning progress (i.e. Kidd et al. 2012; Gottlieb et al. 2013). To explore this question in more detail, it may be of interest in future analyses to plot changes in infants' looking towards experimenters' behaviors and objects across different timepoints in the social interaction, particularly in the *LCHR* condition, in which we would expect infants to decrease their looking to experimenters' objects over time if they are learning that the experimenters' actions (when such actions do occur) are not often congruent with what the infants prefer visually attending to. It may also be of interest to extend the duration of the interactions in the low contingency conditions, to determine whether more extensive experience with aggregating experimenters' low-contingency sensitive or redirective cues would inevitably produce infant social looking preferences and later vigilance patterns analogous to those observed among infants within 10 minutes of exposure to highly contingent sensitive or redirective interaction partners. Such possibilities will need to be explored in further detail.

Regarding the tentative relation we observed between infant unengaged object looking during the experimental social interaction and later vigilance, it may be the case that unengaged object looking is an indicator of relative gaze flexibility during the interaction, as prior work has shown unengaged objects to be less salient for infants typically than objects that social partners are holding or touching (Deák et al., 2014). Given that this correlation was based on a subset of the original sample, we also considered that the randomly-selected subsample of infants from the *HCHR* group (who had more overall looking at unengaged objects) may have been driving the correlation, though further exploration (Supplemental Figure S2.1) has suggested that this is not the case. It will be intriguing to follow up further on this finding, for while it makes sense that more time spent looking at less salient stimuli would predict lower vigilance, it would also be of interest to explore how long infants maintained gaze on these less salient stimuli during each bout of fixation in order to properly examine ideas of exploitation and exploration present in the LC-NE literature (Aston-Jones & Cohen, 2005).

Our finding that social partners' overall response levels directly predicted infant arousal on the Cued Attention task is also in line with prior work assessing the influence of contingent social responding on infants' sensitization to audiovisual stimuli in subsequent habituation tasks (Dunham et al., 1989). However, the direction of our effect is somewhat dissimilar, as infants receiving contingent stimulation in Dunham's (1989) study were more sensitized to (or "engaged in") the task than infants receiving non-contingent stimulation. On this note, differences between Dunham et al.'s (1989) prior work and the current study should be addressed before continuing with our interpretation of our findings. First, while Dunham et al. (1989) assessed experimenters' responding to infants' vocalizations specifically, our study instructed experimenters to respond both to vocalizations and shifts of gaze, which occur much more frequently given that infants (in their waking hours) are nearly constantly looking and shifting gaze to new areas of focus. Thus, while Dunham et al. (1989) was able to clearly assess the effects of social contingency vs. overall levels of behavior on infant arousal using matched noncontingent (*yoked control*) schedules, experimenters' contingency levels in our study are very highly correlated with overall response levels ($r$=.57-.87 between contingency variables and overall rates of responding), making it difficult for us to determine whether the main effect of experimenters' contingency schedules on infants' subsequent arousal is due to higher levels of contingency *specifically* compared to higher overall responsiveness. This is a primary limitation of our current work, and future studies should more systematically explore the relative effects of contingent vs. non-contingent response content variation on infants' subsequent vigilance and arousal (perhaps also by using yoked-control paradigms). It may also be the case that different types of contingency ( i.e., contingency to vocalizations vs. contingency to infant looks) may have differing effects on arousal, with contingency to vocalizations encouraging arousal and engagement more readily than contingency to looks (Goldstein et al., 2010). Further work is needed to explore these possibilities.

Another more general limitation of our current study is that while we obtained measures of vigilance from our infants following exposure to novel social interactions, we do not have baseline data from which to interpret what "high" and "low" vigilance scores on our indices mean in the context of natural arousal variation. It would be of potential interest to gather such baseline data so as to compare whether infants showing high vigilance in our dataset are showing signatures of "hypervigilance" in comparison to moderate or low vigilance (Aston-Jones et al., 1999). Gathering physiological measures of arousal, such as salivary alpha amylase, pupil dilation, or skin conductance measures (e.g. de Barbaro et al., 2017; Granger et al., 2006; Murphy, Robertson, Balsters, & O'connell, 2011), would also be of interest, in order to more closely associate our behavioral indices of vigilance with real-time changes in biological measures peripherally associated with arousal. These are just a few of many possible ways in which this study can be improved and expanded upon in the future.

Overall, our study is one of the first to attempt to assess the effects of both social responsiveness and social content on infant arousal and attention using a neurobiologically-informed theoretical approach. While more work is necessary, we hope that this contribution will help to inspire further efforts to understand underlying mechanisms of social influences on attention and learning in infancy and throughout early development.

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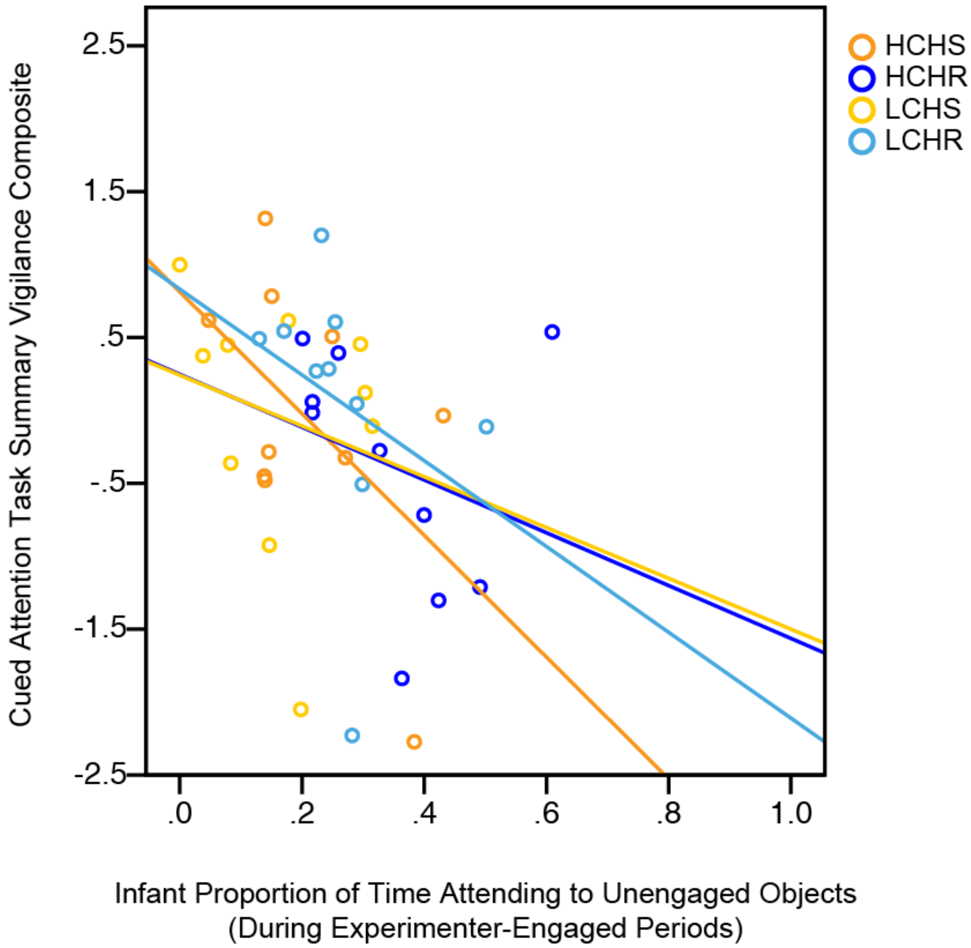


*Supplemental Figure S2.1*. Preliminary exploration (n=40) of relations between infants' unengaged object looking during their social interaction with an unfamiliar experimenter and infants' subsequent vigilance on the Cued Attention Task. The x-axis denotes infants' relative proportion of time spent looking at unengaged objects during moments in which experimenters were touching, holding and/or manipulating at least one object. Dark orange indicates infants exposed to highly contingent/highly sensitive social partners; dark blue shows scores and proportional looking time for infants exposed to highly contingent/highly redirective social partners; light orange portrays infants exposed to low contingency/highly sensitive social partners; and, light blue depicts infants exposed to low contingency/highly redirective social partners.

Supplemental TABLE S2.1.
Interrater Reliability Statistics for Individual Infant and Caregiver Variables

| *Measure* | **ICC Coder 1*** | **ICC Coder 2*** | **ICC Coder 3*** |
|---|---|---|---|
| **Infant relative looking durations during experimenter-engaged periods (to objects, experimenter, caregiver, other, uncodable)** | .95 | .98 | .995 |
| **1.** *Engaged objects* total looking time | .96 | .99 | .99 |
| **2.** *Unengaged objects* total looking time | .96 | .98 | .93 |
| **3.** *Experimenter* total looking time | .94 | .97 | .996 |
| **Infant relative looking durations during unengaged periods (to objects, experimenter, caregiver, other, uncodable)** | .97 | .99 | .97 |
| **1.** *Objects* total looking time | .96 | .99 | .98 |
| **2.** *Experimenter* total looking time | .98 | .98 | .93 |
| **Infant gaze shifts (during engaged and unengaged periods)** | .86 | .93 | .94 |
| **1.** Shifts during experimenter object-*engaged* periods only | .89 | .97 | .98 |
| **2.** Shifts during experimenter object-*unengaged* periods only | .78 | .85 | .90 |

*All coders were compared to the first author's reliability annotations, and all correlations were significant at $p<.05$

**S 2.2. Appendix:**

A1: Pilot Social Response Schedules for Experimental Conditions

| High Contingency, High Sensitivity PILOT Schedule | |
|---|---|
| r | Sensitive |
| r | Redirective |
| r | Sensitive |
| r | Sensitive |
| r | Sensitive |
| r | Sensitive |
| r | Sensitive |
| r | Redirective |
| r | redirective (go back to beginning) |

| High Contingency, High Redirectiveness PILOT Schedule | |
|---|---|
| r | redirective |
| r | redirective |
| r | sensitive |
| r | redirective |
| r | redirective |
| r | redirective |
| r | sensitive |
| r | redirective |
| r | sensitive (go back to beginning) |

| Low Contingency, High Sensitivity PILOT Schedule | |
|---|---|
| nr | no response |
| r | Redirective |
| r | Sensitive |
| nr | no response |
| nr | no response |
| nr | no response |
| nr | no response |
| nr | no response |
| nr | no response |
| r | sensitive (go back to beginning) |

| Low Contingency, High Redirectiveness PILOT Schedule | |
|---|---|
| nr | no response |
| nr | no response |
| nr | no response |
| r | redirective |
| nr | no response |
| r | sensitive |
| nr | no response |
| nr | no response |
| r | redirective |
| nr | no response (go back to beginning) |

A2: Finalized Experimenter Response Schedules

| High Contingency, High Sensitivity | |
|---|---|
| r | Sensitive |
| r | Sensitive |
| r | Sensitive |
| r | Sensitive |
| r | Sensitive |
| r | Redirective |
| r | sensitive |
| r | sensitive |
| r | sensitive |
| r | sensitive (go back to beginning) |

| High Contingency, High Redirectiveness | |
|---|---|
| r | Redirective |
| r | Redirective |
| r | Redirective |
| r | Redirective |
| r | Redirective |
| r | Sensitive |
| r | Redirective |
| r | Redirective |
| r | Redirective |
| r | redirective (go back to beginning) |

| Low Contingency, High Sensitivity | |
|---|---|
| r | sensitive |
| r | sensitive |
| nr | no response |
| nr | no response |
| nr | no response |
| nr | no response |
| nr | no response |
| nr | no response |
| r | sensitive |
| nr | no response |
| nr | no response |
| nr | no response |
| nr | no response |
| r | sensitive |
| r | redirective |
| nr | no response |
| r | sensitive |
| nr | no response |
| nr | no response |
| nr | no response |
| r | sensitive |
| r | sensitive |
| nr | no response |
| nr | no response |
| nr | no response |
| nr | no response |
| nr | no response |
| nr | no response |
| r | sensitive (go back to beginning) |

| Low Contingency, High Redirectiveness | |
|---|---|
| r | redirective |
| nr | no response |
| nr | no response |
| r | redirective |
| nr | no response |
| nr | no response |
| nr | no response |
| nr | no response |
| nr | no response |
| r | redirective |
| nr | no response |
| nr | no response |
| r | redirective |
| r | sensitive |
| nr | no response |
| nr | no response |
| r | redirective |
| nr | no response |
| nr | no response |
| nr | no response |
| nr | no response |
| r | redirective |
| nr | no response |
| nr | no response |
| nr | no response |
| nr | no response |
| nr | no response |
| nr | no response |
| r | redirective |
| r | redirective (go back to beginning) |

# CHAPTER 3.

# EARLY SOCIAL ATTENTION, PARENT-INFANT COORDINATION, AND LEARNING OUTCOMES AMONG INFANTS WHO DEVELOP AUTISM

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## Abstract

In autism spectrum conditions (ASD), differences in social abilities such as joint attention and communication are commonly characterised as primary features of the core phenotype. Within typical development, such social skills are often facilitated by early interactions with caregivers, as caregivers' prompt (*contingent*) and jointly focussed (*sensitive*) responses to infants' prelinguistic vocalizations aid communicative learning. However, it is less known whether these same aspects of interaction relate to social outcomes in infants who develop ASD, as well as whether individual differences in infant visual attention and social responsiveness predict ASD diagnosis. In the present study, we used an unstructured 6-minute free-play paradigm to observe the social attention patterns, vocalizations and interaction dynamics of 6-10-month-old infants at high familial risk of autism and their caregivers. At 36 months, infants were evaluated for ASD, and participated in the Mullen Scales of Early Learning (MSEL) to assess broader language, motor and cognitive development. We found that at 6-10 months, infants who later developed ASD (*HR-ASD* infants) exhibited social looking preferences and responses consistent with those of at-risk typically developing infants (*HR-TD*) and infants with sub-threshold symptoms (*HR-Atyp*). Caregivers of *HR-ASD* infants also did not differ systematically from caregivers of other at-risk infants in their rates of contingent sensitive responding. However, caregivers' contingent sensitive responding to infants' vocalizations positively predicted broader 36-month MSEL scores in *HR-ASD* infants, whilst responding was uncorrelated with learning in *HR-TD* and *HR-Atyp* infants. Our findings suggest that infants who develop ASD may be differentially affected by caregiver feedback compared to infants who do not, and provide new insights into possible social mechanisms of learning in ASD.

Early social attention, parent-infant coordination, and learning outcomes among infants who develop autism

During infancy, rapid progress in social and communicative development emerges in the context of reciprocal social interactions with caregivers and other social partners (Beebe, Lachmann, & Jaffe, 1997; Deák, Triesch, Krasno, de Barbaro, & Robledo, 2013; Goldstein & Schwade, 2008). As infants act on the environment through looking, moving, and vocalizing, their actions elicit responses both from their own sensory systems (Byrge, Sporns, & Smith, 2014; Smith, Jayaraman, Clerkin, & Yu, 2018), and from the adults surrounding them (Gros-Louis, West, Goldstein, & King, 2006; Yu & Smith, 2012, 2016). When infants' actions and adults' responses are coordinated in timing and content, such responses can have beneficial effects on infant learning, particularly in the contexts of social attention and language (Baumwell, Tamis-LeMonda, & Bornstein, 1997; Deák et al., 2013; Goldstein & Schwade, 2008; Goldstein, Schwade, Briesch, & Syal, 2010; Yu & Smith, 2017a).

In autism spectrum conditions (ASD), impairments in aspects of social attention and communication are often reported, with language difficulties also being cited as a common early indicator of the condition (Dawson et al., 2004; Landry & Loveland, 1988; World Health Organisation, 1992). Given that children's communicative and cognitive abilities change significantly over their first few years, recent studies of ASD have focussed on identifying biomarkers and creating interventions during developmental periods that precede reliable ASD diagnosis, including early infancy (Dawson et al., 2012; Jones, Dawson, Kelly, Estes, & Webb, 2017; Webb, Jones, Kelly, & Dawson, 2014). These efforts have been aided by the finding that infant siblings of children with ASD are at an increased risk of developing ASD themselves

(Rogers, 2009; Sandin et al., 2014), as these infants may be identified early and monitored for differences in social and communicative behaviour prior to the full onset of ASD.

Among the early behaviours assessed in at-risk infants, measures of social attention have been of particular intrigue (e.g., Elsabbagh et al., 2013; Jones & Klin, 2013). However, experimental findings have been mixed regarding whether infants who develop ASD show any clear differences in social attention behaviours prior to diagnosis (see Guillon, Hadjikhani, Baduel, & Rogé, 2014 for review). Additionally, whilst many of these findings have been derived from studies assessing social attention in terms of face or gaze processing in highly controlled paradigms (Guillon et al., 2014), less is known about how at-risk infants' social attention manifests in more natural and embodied social interaction contexts. Exploring such processes within the framework of infants' everyday interactions with caregivers is critical, particularly if we are to develop ecologically-informed interventions and models of early social learning in ASD.

*New Approaches to Studying Social Attention in ASD: Considering Naturalistic Findings from Typical Infants*

Recent work on the typical emergence of social attention in naturalistic settings suggests that infants' attention to others' faces and eyes (a commonly used metric of social attention in laboratory paradigms) vary widely with age and context (Fausey, Jayaraman, & Smith, 2016; Jayaraman, Fausey, & Smith, 2015). Considering the specific case of parent-infant free play, social attention appears to manifest more frequently in the form of infants' attention to objects that caregivers are holding or touching, rather than through infants' attention to caregivers' faces or eyes (Deák, Krasno, Jasso, & Triesch, 2018; Deák, Krasno, Triesch, Lewis, & Sepeta, 2014;

Yu & Smith, 2017a, 2017b). In a cross-sectional study of this phenomenon, Deák and colleagues (2014) found that across the first year (from 3-11 months), typically-developing infants spend more time attending to caregivers' held objects during play than to any other looking area, including the sum total of their caregivers' faces, hands and bodies. Additionally, during the few moments in which infants *do* glance at their caregivers' faces, caregivers' faces are also often directed to their own held objects. From these findings and others (Deák et al., 2018; Yu & Smith, 2017b), current theories of social attention development have posited that infants may learn more advanced social attention skills such as gaze following from an initial looking preference for caregivers' held objects, coupled with dyadic experiences in which they learn that their caregivers' gaze is predictably aligned with their preferred sights. These theories provide a novel framework for which to study social attention development in at-risk infants, as differences in more advanced social attention skills (i.e. gaze following) could be due to differences in earlier precursor behaviours and preferences. Such precursor behaviours may include looking preferences for caregivers' objects, as well as the proclivity to shift gaze towards caregivers' attention-directing manual and multimodal actions (Deák et al., 2018).

*Caregiver-Infant Social Coordination Aids Attention and Communicative Learning*

Another benefit of exploring infant social attention in naturalistic settings is that we can observe how different forms of caregiver feedback also help to facilitate infant attention and social learning. As previously noted, infant social attention and communicative skills do not emerge in isolation; rather, they arise from a bidirectional interplay involving infants' own immature behaviours and caregivers' responses, the sensory consequences of which are continually registered by both members of the dyad (Jaffe et al., 2001). One aspect of caregiver responding that seems particularly important for early social development is the *timing* of caregivers' responses relative to infants' behaviours (Goldstein & Schwade, 2008; Goldstein et al., 2010; Yu & Smith, 2012, 2016). In the case of communicative learning, infants appear to learn aspects of language more readily when caregivers' verbal feedback comes within a prompt and reliable (contingent) timeframe with respect to infants' own prelinguistic vocalizations (Goldstein & Schwade, 2008). Additionally, infants' learning of object labels are enhanced when caregivers provide such labels contingently on infants' attention-related ("object-directed") vocalizations (Goldstein et al., 2010) as well as during moments in which the object to be labelled is visually prominent in the infant's field of view (Yu & Smith, 2012).

However, it is often not sufficient for caregivers' behaviours to simply be contingent. Studies in both typical and atypical development have shown that the *content* of caregivers' behaviours also matters for social learning (Baker, Messinger, Lyons, & Grantz, 2010; Baumwell et al., 1997; Goldstein & Schwade, 2009; Goldstein et al., 2010; Yu & Smith, 2016). This idea is corroborated by the finding that infants whose caregivers respond contingently but with contextually irrelevant feedback show reduced language learning, relative to infants whose caregivers respond both contingently and jointly with infants' focus (Goldstein & Schwade, 2009). Such joint feedback, in which caregivers' responses are aligned in space and/or meaning with what the infant is attending to, has been referred to as *sensitive responding* (Baumwell et al., 1997), a term that has also been used to encompass various macro-level constructs related to dyadic coordination (Baker et al., 2010; Mesman, 2010). Within the framework of social attention, typically-developing infants have been shown to respond positively to contingent sensitive responding, extending their gaze on objects that caregivers have recently joined them in attending to (Yu & Smith, 2016). Other experimental work has drawn connections between contingent sensitive responding and increased social attentional engagement among infants (Miller & Gros-Louis, 2017), whilst longitudinal studies have associated contingent sensitive responding in infancy with improved language outcomes at later ages (Baumwell et al., 1997)

*Caregiver-Infant Coordination in ASD*

Whilst the effects of caregiver-infant interaction on social development have been studied widely in typical infants, less is known about how infants' and caregivers' naturally-occurring dyadic behaviours relate to social outcomes for individuals at high risk for ASD. Recently however, a few studies have assessed how microstructural caregivers' and infants' mutual coordination might relate to social development (Northrup & Iverson, 2015; Warlaumont, Richards, Gilkerson, & Oller, 2014). One study found that caregivers of young children with ASD tended to be less selective in their contingent responding to their children's vocal productions, and also that children with ASD tended to produce fewer speech-related vocalizations (Warlaumont et al., 2014). Another study suggested that the timing of vocal turn-taking among high-risk infants and their caregivers was less coordinated, but only among those with later language delay (Northrup & Iverson, 2015). Though both of these studies assessed the moment-by-moment timing and structure of caregivers' and infants' behaviours in a dyadic context, they did not explicitly assess the *content* of caregivers' responses relative to infants' visual attention. In contrast, studies that have endeavoured to evaluate the content of caregivers' behaviours have often done so using macro-level approaches, in which observers score caregivers' and infants' global characteristics on rating scales over the entirety of the social interaction. Such studies have produced mixed results, with some finding differences in constructs such as dyadic mutuality and infant social attentiveness among infants who develop

ASD (Wan et al., 2013) whilst others have found no systematic differences in global measures of caregiver behaviour among ASD vs. no-ASD dyads (Baker et al., 2010).

*The Current Study*

In the current study, we add to recent literature exploring the dynamics of caregiver-infant interaction among infants at high familial risk for autism (Baker et al., 2010; Northrup & Iverson, 2015; Wan et al., 2012, 2013; Warlaumont et al., 2014), with the goal of connecting early infant social behaviours and caregiver feedback with later ASD outcomes. Specifically, we aim to investigate the following:

**Do infants who develop ASD differ in their early social looking preferences from other at-risk infants?** Given recent literature suggesting that the emergence of social attention skills depend on infants' attention to caregivers' held objects, one unanswered question regarding attention in young at-risk infants is whether infants who later develop ASD show differences social object looking compared infants who do not develop ASD. A related question is whether infants who develop ASD will orient to caregivers' held objects during moments in which caregivers are attempting to elicit (redirect) their attention. Though experimental studies of infant face and gaze processing in ASD have produced mixed findings, we hypothesise that infants who go on to develop ASD may show early differences in social object looking preferences. These differences could manifest either as: 1) a lack of clear preference for caregivers' objects, or 2) an atypically heightened interest in caregiver-manipulated objects. Either of these possibilities may work to reduce infants' likelihood of associating their caregivers' gaze with visually-rewarding sights, as 1) would reduce infants' perception of caregivers' object-directed gaze as interesting, whilst 2) may reduce infants' likelihood of pausing to attend to caregivers' faces, and observe their caregivers' visual attention to objects.

**Do infants who develop ASD differ in their moment-by-moment reactions to caregivers' contingent social cues, compared to other at-risk infants?** As noted above, another question of interest is whether infants who develop ASD will attend differently to caregivers' cues. One cue of interest is caregiver's redirections, in which caregivers attempt to guide infants to new areas of focus. Given prior work assessing the effectiveness of different caregiver attention bids on directing infants' attention (Deák et al., 2018), it may be that whilst infant who do not develop ASD are effectively redirected through multimodal cues such as object handling and verbal solicitations, that infants who go on to develop ASD will show reduced responsiveness (or hyperresponsiveness) towards these same cues. Aside from redirections, we are also interested in whether infants who develop ASD use caregivers' sensitive cues to extend their attention, as has been shown in typical infants (Yu & Smith, 2016). If infants who develop ASD are generally hyporesponsive to caregivers' actions, we would not necessarily expect them to differentiate between sensitive and other caregiver behaviours with respect to attentional maintenance, whereas hyperresponsiveness to caregivers' sensitive behaviours could lead to longer attentional maintenance in the context of sensitive responding.

**Are certain caregiver behaviours related to more optimal outcomes among at-risk infants, particularly those that develop ASD?** Finally, though caregivers' contingent sensitive responding has been related to enhanced language and cognitive outcomes in typical infants (Baumwell et al., 1997; Goldstein et al., 2010; Hirsh-Pasek & Burchinal, 2006), it is unclear whether these behaviours would predict enhanced social learning and cognition in ASD. A previous study assessing caregiver sensitivity on a global level among at-risk dyads found a positive relation between sensitivity and ASD children's later language scores (Baker et al., 2010). Intriguingly however, caregiver sensitivity was also positively associated with increased behaviour difficulties in these children, and sensitivity was unrelated to language scores in the non-ASD sample in this study. As we are uncertain how our micro-analytic measures of contingency and sensitivity relate to the global sensitivity ratings using in Baker et al. (2010), it is thus difficult to predict whether caregiver sensitivity (as we have operationalized it) will relate to improved learning and cognition in ASD. However, from a perspective of differential susceptibility, in which genetic atypicalities produce increased susceptibility to environmental influences (Belsky, Bakermans-Kranenburg, & van IJzendoorn, 2007; Belsky & Pluess, 2009), it may be possible that caregiver contingency and sensitivity will relate more strongly to the cognitive outcomes of infants who develop ASD compared to those who do not.

As described above, prior studies on caregiver-infant social interaction in ASD have used various methods to define the structure of infants' and caregivers' social dynamics, with some adopting a more *microstructural* approach (defining precise rates, timings, and counts of different behaviours of interest, often assessed moment-by-moment; e.g. Northrup & Iverson, 2015; Warlaumont et al., 2014; Yirmiya et al., 2006) whilst others have employed more macro-level measures, including rating-scale judgments of content-related interaction constructs (e.g. Baker et al., 2010; Wan et al., 2012, 2013). The methods that we employ here are more in line with the former (micro) measures; however, the questions we endeavour to explore are unique, in that they are informed by recent theoretical models on alternative pathways to social attention and communicative development. We anticipate that our findings will help delineate the social attention dynamics of at-risk infants in the context of caregiver-infant interaction, and that we may also uncover patterns of social feedback that are associated with improved social-cognitive outcomes in children both with and without ASD.

## Method

### *Participants*

To assess the attentional characteristics of infants at risk for ASD during social interactions, data were collected from forty-six 6-10-month-old infants at high risk for ASD (26 female, 20 male; mean age 232.3 days, range 183-334 days) and one of their primary caregivers (all caregivers participating in this sample were the mothers of the infants). These dyads were recruited as part of Phase 1 of the British Autism Study of Infant Siblings (BASIS), a multi-site research collaboration across the United Kingdom dedicated to evaluating infants at high risk for autism. In order to be classified as high risk, infants were required to have at least one older sibling or half-sibling with a community clinical diagnosis of ASD, which was additionally verified through independent evaluation when possible by two expert clinicians associated with the BASIS project. Eight additional high-risk infants were recruited for Phase 1, but were excluded from the present analyses either because they were not able to finish the social interaction assessed in this study (i.e., the social interaction was either not attempted or stopped prematurely; n=6), or due to technical difficulties during video recording of the interaction (i.e., sound loss and video inconvertibility; n=2). Aside from being classified as high-risk, infants had no known medical or neurodevelopmental diagnoses at the time of initial data collection.

Caregiver responsiveness variables (described in more detail under "Coding" below) were also collected when possible from the 46 mother-infant dyads above. Whilst physical object manipulations were collected for all, use of a second language among 3 mothers, combined with low amplification of the audio, inhibited complete collection of more language-dependent caregiver responsiveness measures among these 3 dyads. Thus, the final sample of dyads used in analysis of infant behaviour and caregiver object manipulation was n=46, while the final sample used in analysis of caregiver verbal/multimodal responsiveness was n=43. Additional demographic variables for the entire cohort of at-risk infants and their caregivers are described in previous work (Wan et al., 2012, 2013).

Additionally, for the main analyses of this study, infants were assigned into one of 3 possible groups based on their later diagnostic outcomes (more details on group classification criteria are described under *Materials and Measures* below). These groups included high risk, typically-developing (*HR-TD*; n=19); high risk, atypically-developing (*HR-Atyp*, n=11); and, high risk, diagnosed with ASD (*HR-ASD*, n=16). Children in these groups did not differ with respect to demographic variables including their age at first visit (*HR-TD* mean age= 221.63 days, s.d.= 34.66 days; *HR-Atyp* mean age= 242.91 days, s.d.=36.63 days; *HR-ASD* mean age= 237.69 days, s.d.= 41.08 days) or their age at 3-year follow up (*HR-TD* mean age= 37.26 months, s.d.= 1.66 months; *HR-Atyp* mean age= 36.45 months, s.d.= 1.75 months; *HR-ASD* mean age= 37.56 months, s.d.= 2.13 months). However, sex distribution among these groups differed, as 11 out of 16 infants in the *HR-ASD* group (68.8%) were males, whereas only 3 out of 11 (27.3%) and 6 out of 19 (31.6%) were males in the *HR-Atyp* and *HR-TD* groups respectively. For this reason, in addition to evaluating our hypothesised variables of interest, we included sex as a control variable in subsequent supplemental analyses. Unless otherwise noted, including sex as a factor did not significantly alter the main findings; thus, for ease and clarity, the original analyses are reported in the main text below.

*Materials and Measures*

Caregiver-infant interaction at 6-10 months. For the free play activity, caregivers and their infants were recorded in a laboratory playroom containing a large rectangular playmat, a cardboard box, and two cameras. The cardboard box contained a standard set of toys (rattles, stuffed animals, a baby book, etc.), which were judged to be appropriate for this age range and made accessible for caregivers' and infants' exploration. Infants were unrestrained and placed on the floor with their caregiver during the interaction, to allow for more naturalistic engagement with the caregiver in the context of reciprocal play. Audio and video data were collected together via the two cameras, which were positioned to capture multiple viewing angles simultaneously.

Microstructural coding of caregiver and infant behaviour. The micro-behavioural definitions employed in this study are based on coding schemes described in Mason, Kirkpatrick, Schwade, & Goldstein (2018). These schemes provide comprehensive instructions for quantifying infants' frame-by-frame visual fixation patterns during social interactions, and for enumerating adult social partners' moment-by-moment vocal, behavioural, and multimodal actions in response to infants' vocalizations and "sustained" (>0.5 sec) looks. We utilised these coding schemes as a metric for exploring at-risk infants' early social attentional behaviours during the 6-10 month caregiver-infant interaction, and for determining the degree to which these infants' caregivers provided responses that aligned in timing and/or content with infants' real-time focus. More information on the operational definitions used in this study are described under *Coding* below, and coding manuals are available for public view on Open Science Framework at https://osf.io/tqxrm/?view_only=2b37307cec394cd9b94497a428f0c4cd.

ASD diagnosis at 36 months. Following the 6-10 months visit, children and their caregivers returned at various timepoints (12-15 months, 24 months and 36 months) for follow-up assessments that included several clinical measures of early emerging ASD symptoms. One of the primary measures used in these evaluations included the *Autism Diagnostic Observation Schedule* (ADOS-G; Lord et al., 2000, 1989), which was administered at children's 24- and 36-month visits. The ADOS-G consists of a set of social activities or "presses" that attempt to elicit specific social and communicative behaviours from the child being evaluated, whilst also recording any moments in which restricted or repetitive behaviours and interests are expressed. Alongside the ADOS-G, the *Autism Diagnostic Interview-Revised* (ADI-R; Lord, Rutter, & Le Couteur, 1994) was additionally administered to caregivers during their child's 36-month visit. The ADI-R consists of 93 questions/items that span 3 primary domains (Communication, Reciprocal Social Interaction, and Restricted/Repetitive Behaviours and Interests), and each response is scored by the interviewer on a scale from 0-3 according to the degree to which the interviewee (the caregiver) asserts atypical behaviour to be present.

Using converging data from the measures above, in combination with feedback from clinicians specialising in autism diagnosis (TC, KH, SC and GP), a separate team reviewed each child's data and used a triangulation approach to ascertain whether they met ICD-10 (World Health Organisation, 1992) criteria for an autism spectrum disorder. Given the children's young age at the time of review, the subtypes of atypical autism, other pervasive developmental disorder, and childhood autism were not differentiated, but rather were included within a more general grouping of ASD. Additionally, children who did not meet full criteria for ASD, but whose scores were atypical on at least one diagnostic or broader learning measure were classified as “High Risk- Atypical” (*HR-Atyp*). As described in previous reports on this cohort (Wan et al., 2013), of the 11 who were classified as *HR-Atyp*, 9 met or exceeded diagnostic threshold on at least one ADOS subscale; 1 exceeded threshold on the ADOS, and also scored below 1.5 SD on broader learning measures (the Mullen Scales of Early Learning, described below); and, 1 scored below 1.5 SD on broader learning measures, but did not exceed diagnostic thresholds on the ADOS.

Broader learning measures at 36 months. In addition to ASD outcome classification measures, the Mullen Scales of Early Learning (MSEL; Mullen, 1995) were administered to at-risk children at 36 months to assess broader individual differences in cognitive and motor functioning both within and across ASD diagnostic groups. The Mullen Scales contain tasks for infants and children ranging from 0-68 months that span the domains of Gross Motor, Fine Motor, Expressive Language, Receptive Language, and Visual Reception abilities. Standard T scores and percentiles are derived from each individual scale, and an Early Learning Composite standard score (ELC) is computed to quantify overall level of functioning. The MSEL has been commonly used to assess cognitive abilities in both typical and atypical populations including ASD (e.g. Akshoomoff, 2006), and internal consistency, reliability, and convergent validity with other measures of cognition have been reported previously (Bishop, Guthrie, Coffing, & Lord, 2011; Landa, Gross, Stuart, & Faherty, 2013; Mullen, 1995). The MSEL was administered and scored by trained researchers who were unaware of the current study and hypotheses.

*Procedure*

Procedures for this study were approved by the London Research Ethics Committee (ref: 09/H0718/14), with written informed consent obtained from one or both parents of each child before any assessment or data collection. During infants' 6-10-month visit, researchers recorded at-risk infants and their caregivers as they engaged in a free play session in a laboratory playroom for approximately 6-8 minutes. Caregivers were instructed to play with the infant as they would at home, and were informed that they could use the toys provided if they wished. Otherwise, dyads were given no additional prompts. In the context of the larger visit, the free play session was completed last relative to other tasks, to allow the dyads to become sufficiently comfortable with the testing environment prior to the social interaction.

During infants' follow-up visits, children and their caregivers participated in a variety of tasks similar in scope to those of their first visit. These tasks assessed cognitive, attentional and social development, as well as the presence of ASD characteristics. All procedures during these visits were also in accordance with approved ethics protocols as specified above. Caregivers could stop the sessions and/or take breaks at any time if their child became fussy or upset, and caregivers were reimbursed for any travel expenses related to the visits.

*Micro-behavioural coding*

From the 6-10-month free-play videos, the first author (GMM), who was blind to children's diagnostic outcome, assessed caregivers' and infants' micro-behaviours, including infants' visual and vocal behaviours and caregivers' vocal, behavioural, and multimodal responses. The segments analysed within each video began within the first 30 seconds of experimenters leaving the playroom, and continued for the first 6 minutes following. Events within the videos were identified using ELAN video annotation software, developed by the

Language Archive at the Max Planck Institute for Psycholinguistics in Nijmegen, the Netherlands (Sloetjes & Wittenburg, 2008; https://tla.mpi.nl/tools/tla-tools/elan/).

For infant behavioural coding, infant visual fixations and attention shifts were identified frame-by-frame at 30 frames per second. Attention shifts were counted when infants shifted from one object or category of focus to a different object or category, but were not counted if the infant was fixating or tracking the same item[11]. Infants' visual focus was indexed under one of the following mutually-exclusive categories: *Objects* (toys and other manipulable items; when caregivers were touching or holding objects, this category was further subdivided into *caregiver-engaged* or *caregiver-unengaged* objects, to explore potential differences in infants' attentiveness to caregivers' socially-engaged objects); *Caregiver* (caregiver's face, upper body and hands); *Other/undirected* (including the walls, ceiling, floor, caregiver's legs, and infant's own body); *blink* (moments in which the infant's eyes were closed; these moments were excluded in analyses); and, *non-viewable* (uncodable time, including moments in which the infant's eyes or area of focus were out of view of the cameras; this time was also excluded). Along with infants' visual focus, we identified infants' vocal behaviours throughout the interaction, including non-cry prelinguistic utterances. Such utterances were characterised as *object-directed* (ODV) if, whilst vocalizing, the infant was visually attending to an object. Other vocal categories included *caregiver-directed* vocalizations (CDVs), *other/undirected* vocalizations (UDVs), and *non-viewable* vocalizations (NVs), corresponding to infants' possible looking areas at the time of the vocalization. Vocalizations were excluded if they could be categorised as crying/fussing, or as a vegetative sound (for instance, burps, hiccups, coughs and continuous laughter were excluded). Vocalizations were also excluded if an object was

[11] For a more detailed description of these coding rules, including specific examples, refer to the coding manual available on OSF at https://osf.io/mzgtj/?view_only=2b37307cec394cd9b94497a428f0c4cd

obstructing the infant’s mouth during the vocalization (this is because it can be difficult to determine the acoustic origin of sounds produced during object mouthing, e.g., whether multiple sounds are being produced due to obstructions, or because the infant is producing them independently).

Regarding caregivers’ behaviours, the coder first annotated, frame-by-frame, all moments in which the caregiver handled objects. The coder then went back through the videos and identified all moments in which the caregiver made a verbal utterance during the interaction. For moments in which both object handling and verbalizations occurred simultaneously (or within <0.5 seconds of one another), the coder labelled these occasions as instances of “multimodal” behaviour. After marking the onsets and offsets of caregivers’ behaviours, the coder then determined, based on the content of the caregiver’s behaviour and the visual focus of the infant at the time of the response, whether the caregiver’s behaviour was *sensitive, redirective*, or *non-referential.* In accordance with Mason et al. (2018), caregiver behaviours were *sensitive* if they were congruent spatially and/or semantically with the infant’s visual focus at the time of the response (for instance, providing a label and/or manipulating an object that the infant is visually attending to), and *redirective* if the behaviour attempted to shift the infant’s current focus to a different object or area. *Non-referential* responses were defined as any behaviour that was neither sensitive nor redirective; often, these consisted of vocal statements that did not refer to anything in the immediate environment that infants could readily attend to. Such verbalizations included laughs, exclamations, non-sequiturs, vocal imitations, affirmations, and narrative statements that did not explicitly label the infant’s actions or attentional focus.

After identifying and labelling infants’ and caregivers’ behaviours in ELAN, researchers utilised a combination of hand calculations and automated in-house scripts developed in R and

Python to identify which of caregivers' responses were temporally contingent on infants' behaviours (in line with previous work (Goldstein & Schwade, 2008; Mason et al., 2018; McGillion et al., 2013), caregiver contingency was defined as occurring during, or within 2 seconds following the offset of infants' behaviours). In these analyses, each caregiver behaviour was assigned to only one infant behaviour. Given prior work suggesting that caregiver contingency to infants' vocalizations in particular enhances learning (Goldstein et al., 2010), we examined caregiver contingency with reference to infants' vocalizations specifically, as well as (for comparison) caregiver contingency with reference to any/all coded infant behaviours (including vocalizations as well as "extended" (at least 0.5 sec) visual fixations). Infant variables of interest, including their social looking preferences, attentional reactions to caregivers' responses, and rates of vocalizing, were also calculated via scripts in R and Python, which can be viewed on OSF (https://osf.io/tqxrm/?view_only=2b37307cec394cd9b94497a428f0c4cd).

*Analyses*

Our primary analyses were designed to address 3 main questions: 1) Do infants who develop ASD differ in their early social looking preferences in natural contexts, compared to other at-risk infants? 2) Do infants who develop ASD differ in their moment-by-moment reactions to caregivers' social cues, compared to at-risk infants who do not? And, 3) Are certain caregiver behaviours related to more optimal outcomes among at-risk infants, particularly those that develop ASD?

To examine our first question, we quantified infants' looking preferences by calculating and comparing, both between and within ASD outcome subgroups (*HR-TD, HR-Atyp,* and *HR-ASD*), infants' proportions of total looking time within the categories specified in *Micro-*

*behavioural coding* above. To explore infants' attentiveness to caregivers' cues, we used proportions to quantify how often infants of different subgroups shifted gaze to their caregivers' object of focus contingently in response to caregivers' attention bids (redirective prompts). We also evaluated the relative effectiveness of different response modalities (unimodal vs. multimodal verbal/behavioural bids) on eliciting infants' attention between ASD subgroups, by calculating the proportions of redirections of each modal type that were successful in directing infants to caregivers' objects within 2 seconds. Along with quantifying infants' attentiveness to caregivers' redirections, we also assessed whether infants of different subgroups reacted differently to caregivers' attention-sustaining sensitive responses. To accomplish this, we compared, within infants, infants' average fixation durations following the onset of a caregiver sensitive response, relative to infants' fixation durations during redirective responses and also during non-referential (neither sensitive nor redirective) responses. We used mixed repeated-measures ANOVA analyses to additionally assess infants' average fixation durations between subgroups, and to explore interactions between infants' diagnostic outcomes and caregiver response type in predicting infants' attention durations. Finally, to examine whether specific caregiver-infant interaction characteristics are associated with more optimal cognitive/social outcomes among infants at risk, we first analysed whether caregiver response patterns (% contingency, sensitivity) differ on a group level between different outcome subgroups. We also ran linear model analyses to explore, both within and across subgroups, whether differences in caregiver behaviour at 6-10 months are associated with differences in more continuous measures of cognitive and social skills at later ages (i.e., the MSEL at 36 months). After quantifying individual variables for each dyad using R and Python, we conducted our statistical analyses (ANOVAs, linear models, and follow-up tests) in SPSS.

## Results

*Infant social attention at 6-10 months*

**Do infants who develop ASD differ in their early social looking preferences from other at-risk infants?** Figure 3.1 (a,b) illustrates the relative proportions of time that infants of different diagnostic subgroups spent visually attending to specific areas while interacting with their caregivers. When caregivers were not touching or manipulating objects (Figure 3.1a), infants, regardless of diagnostic outcome, spent their highest proportions of time attending to objects (mean *HR-TD*= 49.46% of total looking time, SD= 21.37%; mean *HR-Atyp*= 61.15% of looking time, SD= 27.92%; mean *HR-ASD*= 52.83% of looking time, SD= 22.14%). Infants' next preferred looking category, again regardless of diagnostic subgroup, was to their caregiver (mean *HR-TD*= 33.33% of looking time, SD= 21.96%; mean *HR-Atyp*= 26.28% of looking time, SD= 25.43%; mean *HR-ASD*= 31.99% of looking time, SD= 20.44%), followed by other/undirected areas (mean *HR-TD*= 17.21% of looking time, SD= 9.93%; mean *HR-Atyp*= 12.57% of looking time, SD= 5.28%; mean *HR-ASD*= 15.18% of looking time, SD= 7.61%). To determine whether infants' looking preferences for objects was significant compared to their next highest looking category, and to assess whether the strength of infants' looking preferences differed between outcome subgroups, we ran a 3 (outcome subgroup) x 2 (looking area: objects vs. caregiver) mixed ANOVA on infants' proportions of looking time[12]. There was a significant main effect of looking area ($F(1,43)= 12.43$, $p=.001$), with no main effect of outcome subgroup, and no looking area x group interaction (both $p$s> .34). These findings suggest that regardless of

[12] As infant looking was evaluated as mutually-exclusive relative proportions, we excluded the looking area that infants attended to the least (other/undirected areas) in this analysis. Doing this allows the summed proportions of the looking areas included (objects and caregiver) to vary sufficiently for the between-subjects term (outcome subgroup) to be evaluated.

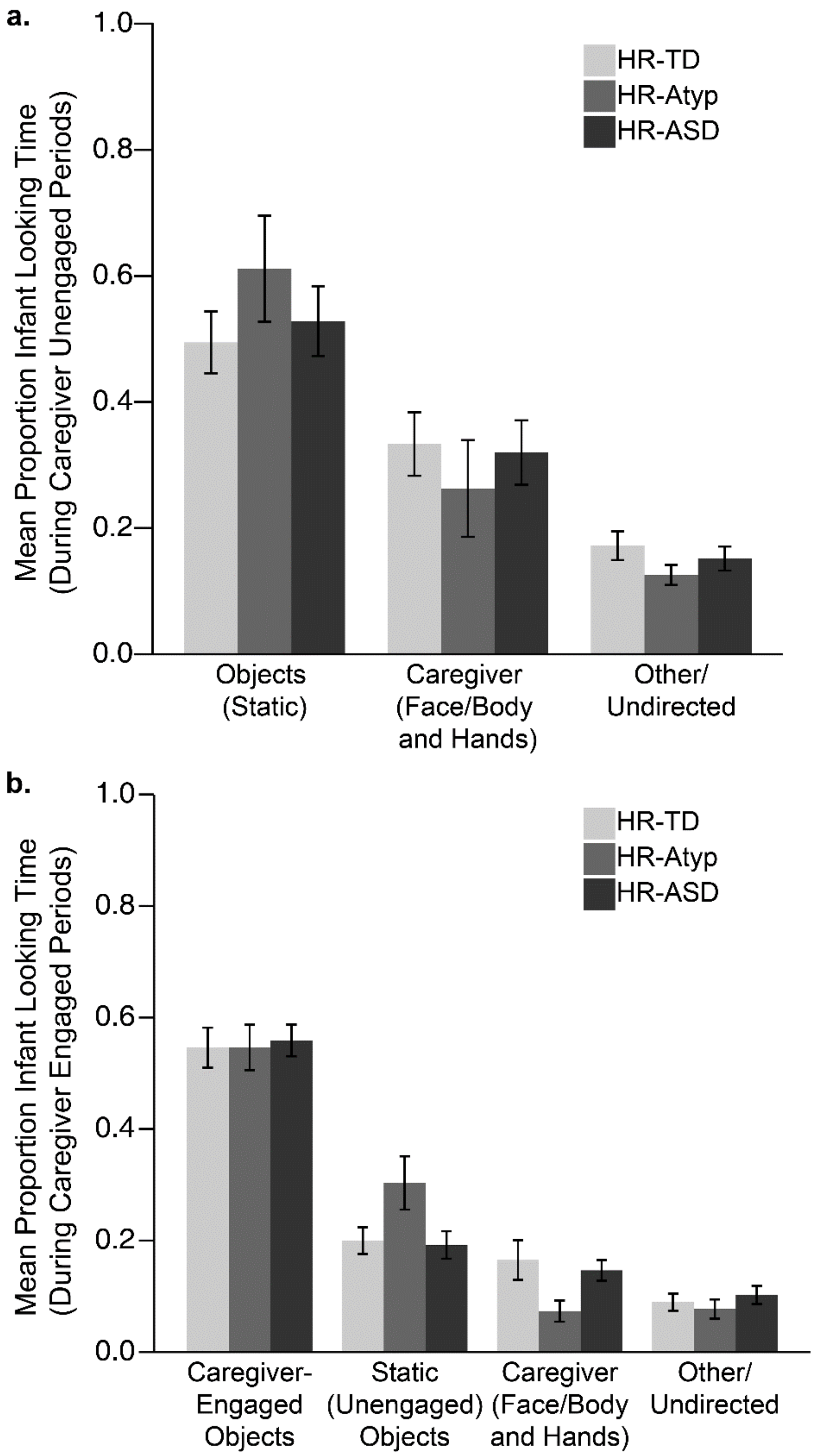



*Figure 3.1*. Infants' relative proportions of looking time at different focal areas during caregiver-infant free play. Graphs depict infant looking when a) caregivers are not touching or manipulating objects, and b) when caregivers are manipulating at least one object. Light grey bars= high-risk, typically-developing infants (*HR-TD*); medium grey= high-risk infants later

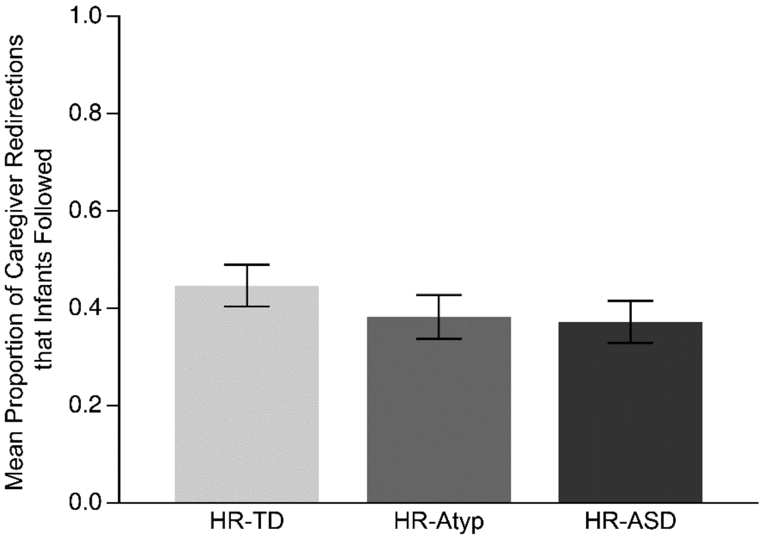
categorised as atypical without ASD (*HR-Atyp*); dark grey= high-risk infants later diagnosed with an ASD (*HR-ASD*).

ASD outcome, infants at 6-10 months prefer attending to objects during moments in which caregivers are not manually engaged with them.

When caregivers were touching or holding objects (Figure 3.1b), infants across subgroups spent over half of their time attending to caregivers' held objects on average (mean *HR-TD*= 54.59% of total looking time, SD= 15.62%; mean *HR-Atyp*= 54.63% of looking time, SD= 13.51%; mean *HR-ASD*= 55.91% of looking time, SD= 11.41%). For all subgroups, infants' next preferred looking category during these periods was *caregiver-unengaged objects*, i.e., objects that the caregiver was not manually manipulating (mean *HR-TD*= 19.97% of looking time, SD= 10.39%; mean *HR-Atyp*= 30.32% of looking time, SD= 15.88%; mean *HR-ASD*= 19.20% of looking time, SD= 9.86%). To explore whether infants within and across groups preferred attending to their caregivers' objects significantly more than to caregiver-unengaged objects, we ran a 3 (outcome subgroup) x 2 (object type: caregiver-engaged vs. unengaged) mixed ANOVA on infants' proportions of looking time. There was a significant main effect of object type ($F(1,43)= 99.86$, $p<.001$), with no significant main effect of outcome subgroup ($p=.14$), and no significant object type x group interaction ($p=.30$), suggesting that infants at 6-10 months significantly preferred attending to caregivers' engaged objects irrespective of later ASD symptomology.

**Do infants who develop ASD differ in their moment-by-moment reactions to caregivers' social cues, compared to other at-risk infants?** In addition to exploring infants' overall looking preferences during natural social interactions, we also assessed whether infants who develop ASD differ from other at-risk infants in how their moment-by-moment attention dynamics are influenced by caregivers' social cues. To investigate this, we first examined whether infants of different outcome groups differed in how often they followed caregivers' redirections to caregivers' objects of focus, by calculating the proportion of caregivers' redirections in which infants oriented to the caregiver's object within 2 seconds (Figure 3.2a). Using a one-way ANOVA with outcome subgroup as the independent variable, we found no significant between-group differences in the proportion of caregivers' redirections that infants successfully followed ($F(2, 40)= .92$, $p=.41$). For all subgroups, it appeared that caregivers' redirections were successful in bringing infants' attention to the redirected object in less than 50% of all cases, when applying a 2-second criterion (Fig. 3.2a). Given the risk status of this group as a whole (and the possible presence of motor difficulties that may affect visual orienting in naturalistic contexts), we decided to additionally assess the successfulness of caregivers' redirections using an extended time window of 5 seconds. Within 5 seconds, *HR-TD* infants successfully followed caregivers' redirections in approximately 53% of all cases on average (mean *HR-TD*= 53.08%, SD= 21.67%), whilst *HR-Atyp* and *HR-ASD* infants continued to follow caregivers' redirections in less than half of cases on average (mean *HR-Atyp*= 46.84%, SD= 17.46%; mean *HR-ASD*= 45.66%, SD= 18.34%). Nonetheless, group differences in successful cue following remained non-significant when assessed via one-way ANOVA ($F(2, 40)= .66$, $p= .52$).

We next assessed whether different redirection *modalities* (verbal-only, behavioural-only, or multimodal verbal/behavioural) elicited cue following differently among infants of different outcome subgroups. Prior to this analysis, we first explored the composition of caregivers' redirections between subgroups using descriptive statistics. Across groups, caregivers' redirections were overwhelmingly multimodal (i.e., they contained both verbal and behavioural a.




b.

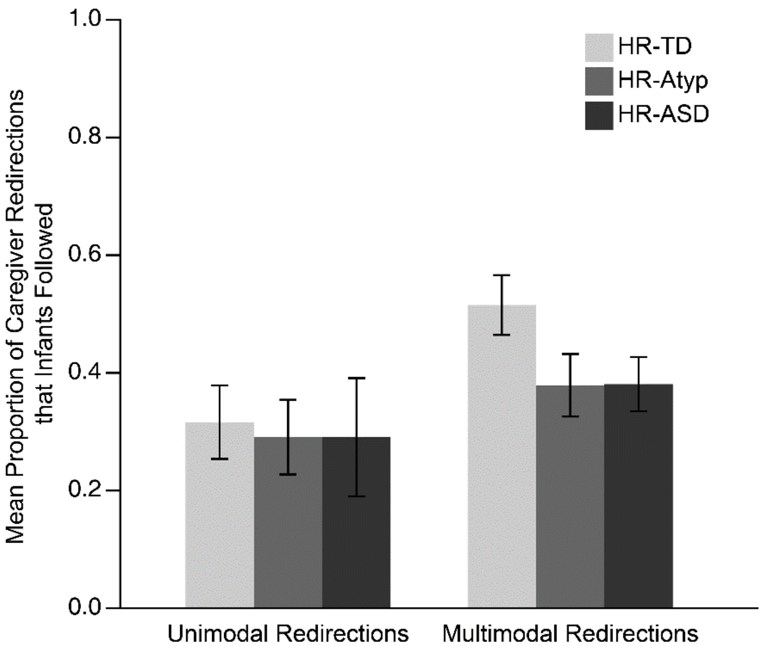



*Figure 3.2*. Social responsiveness of *HR-TD, HR-Atyp*, and *HR-ASD* infants to caregivers' redirective attention bids, measured as the proportion of caregivers' attention bids in which infants successfully attended to the caregiver's object of focus within 2 seconds. a) Depicts the proportion of redirections that *HR-TD, HR-Atyp*, and *HR-ASD* infants followed, regardless of modality. b) Illustrates the proportions of unimodal redirections that infants followed (# unimodal followed/# total unimodal redirections), as well as the proportions of multimodal redirections that infants followed (# multimodal followed/# total multimodal redirections). Across groups, infants responded to a higher proportion of redirections when they were multimodal compared to unimodal ($p$=.02).

elements; mean *HR-TD*= 77.22% of all redirections, SD= 15.51%; mean *HR-Atyp*= 68.10% of all redirections, SD= 18.96%; mean *HR-ASD*= 76.97% of all redirections, SD= 16.49%), and there were no significant between-group differences in the proportions of caregivers' redirections that were multimodal (one-way ANOVA: $F(2,40)= 1.12$, $p=.35$) . Because over half of the caregivers in the dataset (25 of 43) produced 1 or fewer verbal-only redirections, we decided for the present analysis to collapse "verbal-only" and "behavioural-only" redirections into one category of *unimodal* redirections, and to compare caregivers' proportions of successful unimodal redirections (out of all unimodal redirections provided) with caregivers' proportions of successful multimodal redirections (Figure 3.2b). To compare the relative effectiveness of caregivers' unimodal and multimodal redirections both within and between outcome subgroups, we ran a 3 (outcome subgroup) x 2 (redirection type: unimodal vs. multimodal) mixed ANOVA on the proportion of redirections that infants successfully followed within 2 seconds. There was a significant main effect of redirection type ($F(1,38)= 5.92$, $p=.02$), with infants across groups following a greater proportion of redirections when they were multimodal compared to unimodal (Fig. 3.2b). There was no significant main effect of outcome subgroup ($p= .40$), and no significant redirection type x group interaction ($p= .57$).

Aside from evaluating at-risk infants' ability to follow caregivers' redirections, we also explored whether caregivers' *sensitive* (jointly focussed) responses promoted attention maintenance differently for infants who develop ASD compared to other at-risk infants. To assess this, we compared across outcome subgroups the average durations of time that infants maintained attention to their own area of focus following the onset of a sensitive response (Figure 3.3(a-b)). To ensure that any between-group effects observed weren't simply due to differences in infants' overall ability to maintain attention (and to investigate whether caregivers' sensitive responses do, in fact, promote attentional maintenance among infants relative to other caregiver responses), we also compared, within and between groups, the durations of time that infants maintained fixation following *non-referential* responses (responses not hypothesised to necessarily influence attention maintenance in either direction), as well as following *redirective* responses (i.e., responses hypothesised to disrupt attention). Infant fixations were excluded from analysis if more than one caregiver response spanned the duration of the infant's look (for instance, if a sensitive and non-referential response both occurred during the same fixation). Thus, our analysis consisted of a 3 (outcome subgroup) x 3 (caregiver response type: sensitive vs. non-referential vs. redirective) mixed ANOVA on the average durations of time that infants maintained attention after caregivers' response onset. Infants' relative attention durations following each caregiver response type are illustrated in Figure 3.3b. There was a significant main effect of caregiver response type ($F(2, 78)= 8.53$, $p<.001$), with no main effect of outcome subgroup ($p= .65$), and no response type x group interaction ($p= .98$). Follow-up tests (with significance set to $p=.017$ to adjust for multiple comparisons) revealed that across outcome subgroups, infants maintained their attention significantly longer following the onset of sensitive responses than of either nonreferential responses (mean attention duration following *sensitive*= 1.03 sec, mean following *non-referential*= .85 sec; $F(1, 42)=12.44$, $p=.001$) or of redirective responses (mean duration following *sensitive*=1.02 sec, mean following *redirective*= .83 sec; $F$(1, 41[13])=13.14, $p=.001$). There were no significant differences in infants' average attention durations following non-referential responses compared to infants' attention durations following redirections ($F(1, 41)=.032$, $p=.86$).

[13] An additional participant was excluded in this analysis, because all of the redirections that the caregiver provided occurred during uncodable infant looking time.

Though the above analysis suggested that sensitive responses promote increases in focus among at-risk infants regardless of ASD outcome, we realised that the effects we observed might not be due to the content of caregivers' responses *per se*, but rather due to possible systematic differences in the onsets of caregivers' different response types relative to infants' fixation time. Specifically, if caregivers provide sensitive responses consistently *earlier* during infant looks than non-referential or redirective responses, infants' fixation durations following caregivers' sensitive response onsets might appear artificially longer compared to their fixations following other response types. To explore whether this was the case, we ran a one-way ANOVA examining the effect of caregiver response type (sensitive vs. non-referential vs. redirective) on caregivers' latency to respond to infants' looks across outcome groups. Whilst there was a significant effect of caregiver response type on caregivers' latencies to respond ($F(2, 82)= 6.52$, $p=.002$), the direction of the effect contrasted from what would be expected if infants' longer looking following sensitive responses was due simply to earlier sensitive response timings (Figure 3.3c). Specifically, caregivers waited *later* in infants' looking to provide sensitive responses, in comparison to providing non-referential or redirective responses (mean latency to provide a sensitive response= 1.01 sec; mean latency to provide a non-referential response= .85 sec; mean latency to redirect= .80 sec). Pairwise comparisons (using a Bonferroni-adjusted threshold of $p=.017$) suggested that these latency differences were significant between sensitive and nonreferential responses ($F(1, 42)= 6.70$, $p=.013$), and also between sensitive and redirective responses ($F(1, 41)= 17.17$, $p<.001$). Caregivers' latencies to provide non-referential responses did not significantly differ from their latencies to provide redirective responses ($p=.43$). Thus, whilst caregivers waited longer to provide sensitive responses to infants' looks, infants'

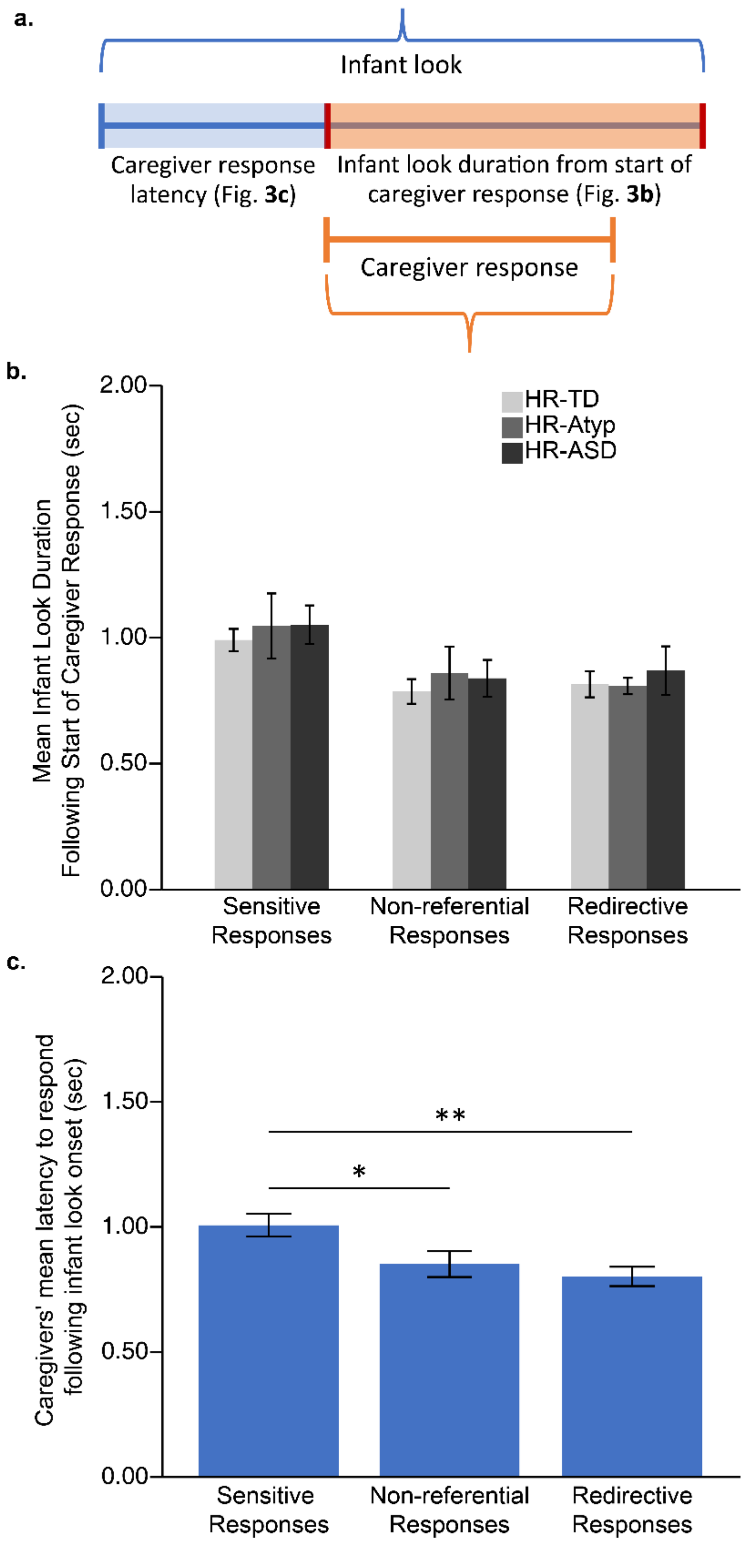



*Figure 3.3*. Dynamics of infant visual attention and caregiver response latencies. a) Hypothetical illustration of an infant gaze fixation interrupted by a caregiver response. To evaluate how different caregiver response types influence infants' sustained attention, we measured the

duration of infants' attention starting from the onset of a caregiver's response and ending at the termination of the infant's look (bar flanked by red vertical lines). b) Mean fixation durations of *HR-TD*, *HR-Atyp*, and *HR-ASD* infants following interruption by either sensitive, non-referential, or redirective responses. There were no significant between-group differences, though there was a significant main effect of caregiver response type, with sensitive response interruptions resulting in extended look durations relative to non-referential and redirective responses. c) Mean latency for caregivers to interrupt an infant look, indexed by caregiver response type. Caregivers waited longer when providing sensitive responses than when providing non-referential or redirective responses. *p<.05; **p<.01

attentional maintenance following the onset of these responses was nonetheless extended relative to their fixation durations following non-referential or redirective responses.

*Caregiver behaviour and ASD outcomes*

**Are certain caregiver behaviours related to more optimal outcomes among at-risk infants, particularly those that develop ASD?** In our final analyses, we aimed to explore whether certain caregiver behaviours observed during the parent-infant interactions at 6-10 months might be associated with enhanced cognitive and social outcomes among at-risk infants, particularly during their time of ASD diagnosis (36 months). As an initial assessment, we examined whether specific characteristics of caregivers' responses (contingency, as well as the content of caregivers' contingent responses) differed on a group level among *HR-TD*, *HR-Atyp*, and *HR-ASD* dyads. Figure 3.4 depicts caregivers' mean levels of contingent responding between outcome subgroups, measured as the proportion of infant behaviours that received a caregiver response. To explore possible differences in caregiver contingency levels between outcome subgroups, we ran two one-way ANOVAs. The first assessed caregivers' levels of contingency to infants' prelinguistic vocalizations alone as a function of outcome subgroup, whilst the other ANOVA analysed caregivers' levels of contingency to all infant behaviours (including visual fixations >0.5 seconds, or prelinguistic vocalizations) as a function of outcome subgroup. Between groups, caregivers of *HR-TD*, *HR-Atyp*, and *HR-ASD* infants did not differ in their

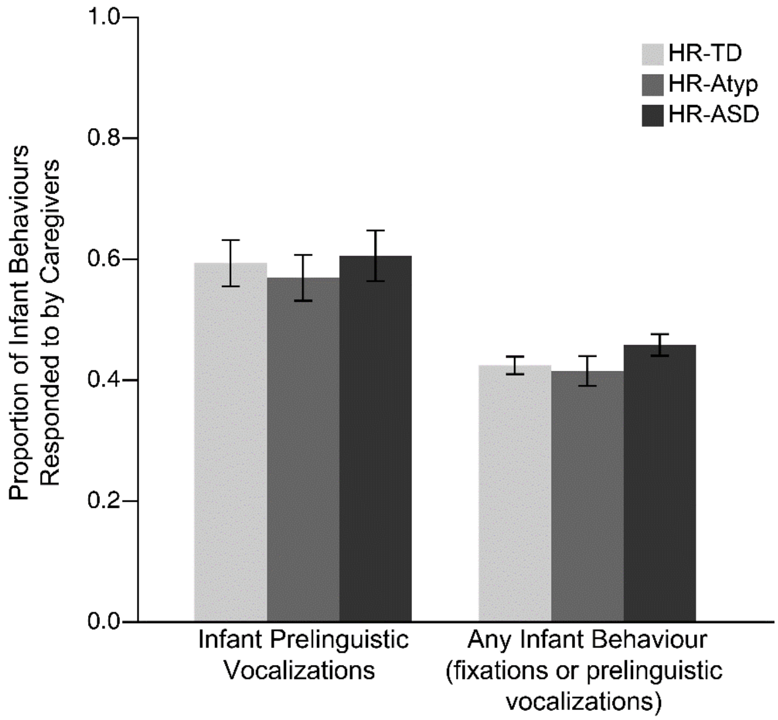



*Figure 3.4*. Caregivers' mean contingency levels among *HR-TD, HR-Atyp*, and *HR-ASD* infants, measured as the proportion of infant behaviours to which the caregiver responded within a 2-second contingency window. There were no significant between-groups differences in caregivers' levels of contingency, whether measured relative to infants' vocalizations or to any infant behaviour.

overall levels of contingent responding, whether it be to infants' prelinguistic vocalizations ($F(2,42)= .16$, $p= .85$) or to all infant behaviours ($F(2, 42)= 1.45$, $p= .25$).

Following these analyses, we next examined whether the *content* of caregivers' contingent responses differed significantly between outcome subgroups. We were particularly interested in the composition of caregivers' responses to infants' prelinguistic vocalizations, given prior research indicating the importance of these responses for early communicative learning (Goldstein & Schwade, 2008, 2009; Goldstein et al., 2010). The content characteristics of caregivers' contingent responses to *HR-TD*, *HR-Atyp*, and *HR-ASD* infants' prelinguistic vocalizations are shown in Figure 3.5a. Across groups, caregivers' contingent responses were

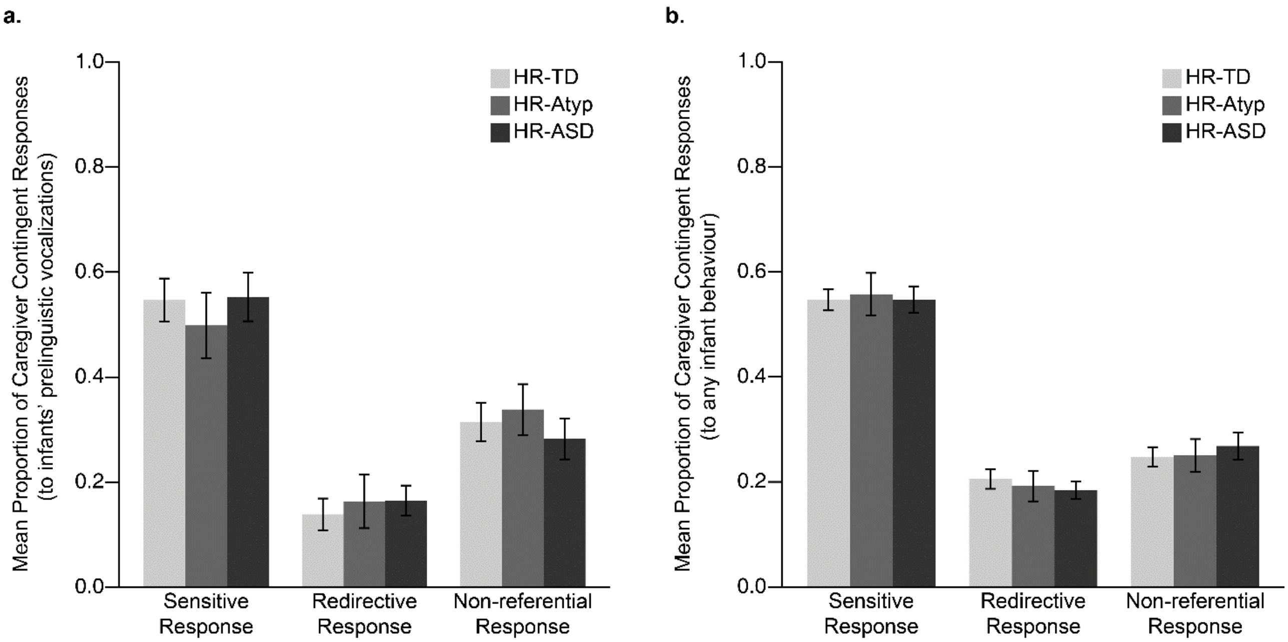



*Figure 3.5*. Content of caregivers' contingent responses to *HR-TD*, *HR-Atyp*, and *HR-ASD* infants' behaviours. a) Displays the content composition of caregivers' contingent responses to infants' vocalizations only, while b) depicts the composition of caregivers' contingent responses to any infant behaviour. Across groups, caregivers provided more sensitive responses than any other type of response.

primarily sensitive, as approximately half of caregivers' responses to infants' vocalizations were sensitive on average (mean *HR-TD*= 54.66% of contingent responses, SD= 18.03%; mean *HR-Atyp*= 49.84% of contingent responses, SD= 19.68%; mean *HR-ASD*= 55.26% of contingent responses, SD= 17.19%). Caregivers' next highest response type across groups consisted of non-referential responses (mean *HR-TD*= 31.46% of responses, SD= 15.77%; mean *HR-Atyp*= 33.84% of responses, SD= 15.29%; mean *HR-ASD*= 28.24% of responses, SD= 14.51%), followed by redirective responses (mean *HR-TD*= 13.88% of responses, SD= 13.12%; mean *HR-Atyp*= 16.32% of responses, SD= 16.07%; mean *HR-ASD*= 16.51%, SD= 10.73%). To evaluate whether caregivers provided significantly more sensitive responses than their second most frequent response type (non-referentials), and whether caregivers' provision of such response types differed by outcome subgroup, we ran a mixed 3 (outcome subgroup) x 2 (caregiver response type: sensitive responses vs. non-referentials) on the proportion of caregivers' responses to infants' vocalizations. There was a significant main effect of caregiver response type ($F(1, 40)= 20.56$, $p<.001$), with no significant effect of outcome subgroup ($p=.82$) and no response type x group interaction ($p=.69$), suggesting that caregivers across outcome subgroups provided significantly more sensitive than other response types in response to infants' vocalizations. A similar pattern was observed when examining the composition of caregivers' responses to any infant behaviour (Figure 3.5b), as sensitive responses were the most prominent among caregivers regardless of outcome subgroup (again, non-referentials were the second most frequently observed). Again using a mixed 3 (outcome subgroup) x 2 (caregiver response type: sensitive responses vs. non-referentials) ANOVA, we found a significant main effect of caregiver response type ($F(1, 40)= 115.15$, $p<.001$), with no main effect of outcome subgroup ($p= .74$), and no response type x group interaction ($p= .92$).

Finally, we explored whether individual variation in caregivers' responses *within* subgroups related to individual differences in at-risk children's later cognitive outcomes. To analyse this, we first evaluated how variation in caregivers' contingent sensitive responses correlated with children's 36-month scores on the MSEL Early Learning Composite (ELC), which includes measures of receptive and expressive language in addition to visual pattern matching and motor ability. When evaluating at-risk dyads as a whole (regardless of outcome subgroup), there were no significant correlations between caregivers' contingent sensitive responses and children's broader scores on the MSEL ELC at 36 months. This was true both when we evaluated caregivers' levels of contingent sensitivity to infants' vocalizations only, and when we assessed caregivers' contingent sensitivity to any/all infant behaviours (all *p*s>.142). However, we suspected that the uniformly higher ELC scores among the typically-developing (*TD*) children in the broader at-risk group might be masking potential positive correlations between sensitive responding and cognitive outcomes in the atypically-developing subgroups (*HR-Atyp* and *HR-ASD*). For this reason, we next assessed whether infants' outcome subgroup affected the strength of the correlation between caregivers' sensitive responding and children's 36-month scores on the ELC, by running separate correlations for each subgroup (Figure 3.6). Among dyads whose children were later diagnosed with ASD (*HR-ASD*), caregivers' levels of contingent sensitive responding to infants' vocalizations were significantly positively correlated with children's 36-month scores on the ELC ($r$= .67, $p$= .012). In contrast, caregivers' sensitivity to vocalizations was not significantly correlated with children's ELC scores among *HR-Atyp* children ($r$= -.41, $p$= .24), nor among *HR-TD* children ($r$= .16, $p$= .52). Additionally, neither overall contingency level (to vocalizations or to all infant behaviours), nor sensitivity to all infant behaviours were significantly correlated with ELC scores in any group (all *p*s >.20).

To further confirm the explanatory power of outcome subgroup and caregiver sensitivity on at-risk children's ELC scores, we ran a General Linear Model (GLM) including 1) *outcome subgroup* and 2) *caregivers' proportion of sensitive responses to infants' vocalizations* as predictors of children's ELC scores at 36 months. Parameter estimates for each predictor, using *HR-ASD* as the reference (omitted) group, are presented in Table 1 (for simplicity of interpretation, caregivers' proportion of sensitive responses were z-standardised for analysis). The overall model was significant ($F$(5, 36)= 5.13, $p$= .001), with an $R^2$ value of .42. There was a significant main effect of outcome subgroup ($F$(2, 36)= 5.26, p=.010), as well as significant main effect of caregiver sensitivity ($F(1, 36)= 4.28$, $p= .046$), and a significant sensitivity x outcome subgroup interaction ($F(2, 36)= 7.12$, $p=.002$). Considering the parameter estimates of the model,

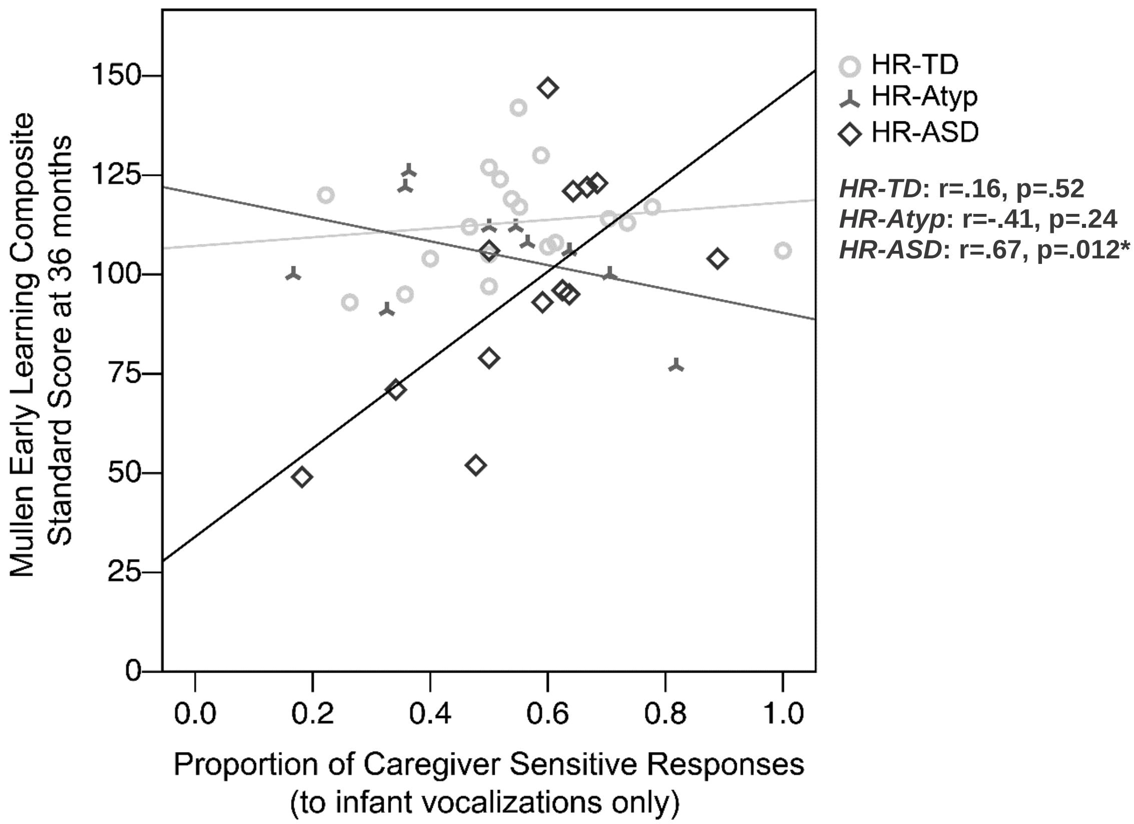



*Figure 3.6*. Correlations between caregivers' sensitivity to infants' vocalizations, and *HR-TD*, *HR-Atyp*, and *HR-ASD* infants' learning outcomes on the Mullen Scales of Early Learning at 36 months. Light grey circles denote *HR-TD* children; three-pointed stars (medium grey) represent *HR-Atyp* children; and, dark grey diamonds depict *HR-ASD* children.

it appeared that whilst children who develop ASD have lower ELC scores than *HR-TD* and *HR-Atyp* children at mean levels or lower of caregiver sensitivity, their predicted ELC scores increase by 19.86 points with each unit increase (measured in standard deviations) of caregiver sensitivity. In contrast, the predicted ELC scores of *HR-TD* children increase only slightly (19.86-17.90= 1.96 points) with each unit increase in sensitivity, and the predicted ELC scores of *HR-Atyp* children decrease slightly (19.86-25.22= -5.36 points) as caregivers' sensitivity increases. Thus, the relation between ASD diagnostic outcome and children's broader cognitive abilities (as measured by the ELC) appears to be moderated, at least in part, by caregivers' sensitive responding to infants' vocalizations.

TABLE 3.1
Parameter Estimates for General Linear Model Assessing the Influence of Group Status and Caregiver Sensitivity on the Mullen Early Learning Composite (ELC)

| ***Variable*** | ***B*** | ***SE B*** | ***t*** | ***P*** |
|---|---|---|---|---|
| **(Constant[a])** | 93.77 | 4.61 | 20.34 | <.001** |
| ***Main Effects*:** | | | | |
| **Caregiver proportion sensitivity to vocalizations (z-standardised)** | 19.86 | 4.89 | 4.06 | <.001** |
| **Group Indicator 1 (*HR-TD*)** | 19.29 | 5.96 | 3.24 | .003** |
| **Group Indicator 2 (*HR-Atyp*)** | 10.46 | 7.03 | 1.49 | .15 |
| ***Interaction Terms*:** | | | | |
| **Caregiver sensitivity x *HR-TD*** | -17.90 | 6.21 | -2.88 | .007** |
| **Caregiver sensitivity x *HR-Atyp*** | -25.22 | 6.96 | -3.62 | .001** |

[a]Note: In this analysis, *HR-ASD* was the reference group.

*Post-hoc/Exploratory Analyses*

Given the significant relation between caregiver sensitivity and 36-month ELC scores within our *HR-ASD* sample, we were interested to explore whether individual variation in the infant social attention and vocalization behaviours that we measured at 6-10 months might also relate to children's ELC scores, and whether such behaviours might moderate the effect of caregiver sensitivity on these scores. Based on prior literature in both typical and atypical infants (Goldstein et al., 2010; Wass et al., 2015), we explicitly wondered whether infants' production of object-directed vocalizations (ODVs), as well as their attention maintenance following caregivers' sensitive responses, might predict enhanced ELC scores. To assess this, we conducted exploratory Pearson's correlations evaluating whether 1) infants' ODV production (measured both as a proportion of total vocalizations that were ODVs, and as infants' rates of ODV production per minute throughout the session) and attentional maintenance following sensitive responses were correlated with their later ELC scores, and 2) whether these same infant behavioural variables also correlated with caregivers' proportions of sensitive responding to vocalizations. The results of these correlations for *HR-ASD* infants, as well as among the entire at-risk sample, are depicted in Supplemental Tables S1 and S2 respectively. As is shown, there were no significant correlations between infants' attention/vocalization variables and 36-month scores on the ELC, nor were there significant relations between these infants' attention/vocalization variables and caregivers' proportions of sensitive responding to vocalizations (among those comparisons, all $p$s>.12). This suggests that the significant positive relation between caregivers' sensitivity and *HR-ASD* infants' 36-month ELC scores is not necessarily moderated by 6-10-month-olds' vocal directedness towards objects, nor by infants' fixation durations in response to sensitive caregiver behaviour at this age.

## Discussion

In the present study, we characterised microstructural patterns of early social attention and interaction among 6-10-month-olds at high risk for ASD and their caregivers, and examined how such patterns may predict later ASD and learning outcomes. Specifically, we used a naturalistic social paradigm (parent-infant free play) to identify at-risk infants' social looking preferences and visual attention to caregivers' cues, as well as the precise timing and content of caregivers' responses to infants' behaviour. We then explored not only the connections between these early behaviours and later ASD diagnosis, but also how these early behaviours predicted variation in cognitive functioning among at-risk children, both with and without later ASD. From our analyses, three main findings emerged. First, infants who were later diagnosed with ASD appeared (at least on a group level) to possess social attention preferences and strategies at 6-10 months akin to those of other at-risk infants who did not develop ASD. Secondly, caregivers of such infants also appeared to have similar levels of contingent responding, and similar variation in the content of their contingent responses, when compared to caregivers whose at-risk infants were not later diagnosed with ASD. Despite the lack of noticeable early differences in behaviour among at-risk dyads whose infants developed ASD, we also found that caregivers' sensitive feedback to infants' vocalizations was more strongly and significantly predictive of 3-year cognitive outcomes in infants who developed ASD than among infants who did not receive an ASD diagnosis. This last finding may suggest (though other interpretations are also explored below) that later cognitive skills among infants who develop ASD may be more heavily affected by, and dependent on, early social support from caregivers than cognitive development in infants who do not develop ASD.

Regarding at-risk infants' social attention patterns, 6-10-month-olds, regardless of later ASD outcome, showed significant looking preferences for objects with which their caregivers were actively engaged (touching or manipulating). Such early preferences for socially-engaged objects have also been reflected in recent studies of typical infant development at this age (Deák, Krasno, Triesch, Lewis, & Sepeta, 2014), and infants' attentiveness to caregivers' held objects has been proposed as an early pathway by which more advanced joint attention abilities may be fostered in complex natural environments (Yu & Smith, 2012, 2017b). Our finding is thus encouraging, as it denotes a possible means by which infants at risk for ASD may continue to build social attention skills during early development. In terms of at-risk infants' social attention *dynamics*, whilst infants did not appear to follow caregivers' redirective attention bids reliably across diagnostic subgroups, these same infants did appear to receive an attention-scaffolding benefit from their caregivers' sensitive responses. This was evidenced by the finding that at-risk infants across diagnostic subgroups maintained their attention for longer periods following the onset of sensitive responses than they did following non-referential or redirective responses. Again, this finding is promising, as it suggests that at-risk infants during this period are able to differentiate and process caregivers' sensitive social cues in ways that immediately benefit their attention. Similar incorporation of caregivers' sensitive cues to support sustained attention has been observed among typical infants as well (e.g. Yu & Smith, 2016), further lending support for the notion that at-risk infants (including those who develop ASD) are exhibiting some degree of typical social behaviour and responsiveness at this age.

Considering caregivers' behaviours, caregivers of *HR-TD*, *HR-Atyp,* and *HR-ASD* infants did not differ in their levels of contingency to infants' vocalizations or other coded actions, nor did they differ in the semantic *content* (sensitivity/joint focus) of their contingent responses when assessed at a group level. Prior studies of caregiver contingency in ASD have suggested that caregivers of infants and children with ASD are perhaps less selective in the behaviours they respond to than caregivers of typically developing children, as their responses are less dependent on whether their child's vocalizations are "speech-related" than are the responses of caregivers of non-ASD children (Warlaumont et al., 2014). Though the lack of difference in caregiver contingency among our diagnostic subgroups may seem counter to this finding, it is crucial to note here that we did not characterise the acoustic quality of infants' vocalizations in this study. Thus, whilst caregivers of *HR-TD*, *HR-Atyp* and *HR-ASD* infants in our study appear to be equally contingent to infants' vocalizations, it may be possible that *HR-ASD* infants are producing vocalizations that are lower in acoustic quality (Patten et al., 2014) than those of *HR-TD* and *HR-Atyp* infants. If this is the case, reinforcing such lower-quality vocalizations may be counterproductive to future speech development (Warlaumont et al., 2014), though more research must be conducted to fully delineate this possibility. Additionally, though Warlaumont et al. (2014) included infant vegetative/regulatory sounds such crying and digestive noises in their analyses of caregiver contingency, we excluded infant crying, coughing, and other vegetative sounds from our contingency analyses. Had we included such actions, we may have found support for Warlaumont et al.'s finding that caregivers of children with ASD are less selective in their contingent responding compared to caregivers of typically-developing children. Finally, as Warlaumont et al. (2014) studied infants and children with ASD over a wide age range (16-48 mos), it may be possible that whilst caregivers of *HR-ASD* infants do not differ in their selectivity of responding when infants are 6-10 months, that they go on to differ in their selectivity at later ages. Additional analyses are needed to address these remaining questions.

Perhaps the most intriguing of our findings is that whilst caregivers across groups had similar variation in the content of their contingent responses, variation in caregivers' contingent sensitivity to vocalizations differentially predicted later learning outcomes for *HR-ASD* infants compared to *HR-TD* and *HR-Atyp* infants. More specifically, caregiver sensitivity was strongly positively correlated with *HR-ASD* infants' 36-month learning scores on the MSEL (a measure of language development, motor skills and visual pattern learning), though sensitivity was uncorrelated with the learning scores of either *HR-TD* or *HR-Atyp* infants. This finding was unexpected, given ample prior research suggesting the benefits of caregiver sensitive responding for both immediate and long term communicative and cognitive outcomes in typical infants (e.g.

Baumwell, Tamis-LeMonda, & Bornstein, 1997; Goldstein et al., 2010; Hirsh-Pasek & Burchinal, 2006). However, our finding does correspond to another prior study suggesting that maternal sensitivity (as measured on a macro-scale) predicted language growth in the MSEL among children with ASD only, when compared to high and low-risk infants without ASD (Baker et al., 2010).

At least for the *HR-TD* infants in our study, the lack of association between caregiver sensitivity and later development could be potentially explained by the overall smaller spread of learning scores we observed among infants in this subgroup (Figure 3.6). Through there was still arguably sufficient variability in *HR-TD* infants' scores to merit analyses, it may be that more specific or challenging learning tasks would elicit greater disparities in performance among *HR-TD* children, which may then highlight the early effects of sensitive responding on children's later outcomes. Another possibility (not mutually exclusive) for why caregiver sensitivity did not relate to learning among both *HR-TD* and *HR-Atyp* infants is that these children may have greater compensatory strategies, or may simply be less influenced by, differences in external environmental variables compared to at-risk children who develop ASD. Such differences in early vulnerability to external variables have been formally theorised as "differential susceptibility" or biological sensitivity to context (Belsky et al., 2007; Ellis & Boyce, 2008), whereby variability in early biological predispositions relates to differences in overall susceptibility (both positive *and* negative) to external influences. Given the wide range of variability in the ELC scores of children with ASD (with individuals in this group possessing both the lowest and *highest* ELC scores within the entire at-risk sample (Fig. 3.6)), it is plausible that the internal biological vulnerabilities that predispose these children to developing ASD also confer heightened early susceptibility to caregiver feedback. This notion is further corroborated by studies suggesting differences in early arousal and norepinephrine-mediated responsivity in infants and children who develop ASD (Blaser, Eglington, Carter, & Kaldy, 2015; Gliga et al., 2015; Wass et al., 2015), as differences in arousal systems have been proposed to mediate children's differential susceptibility and sensitivity to context (Ellis & Boyce, 2008).

Of course, there are other possible explanations for the above finding, and these explanations highlight one of our study's primary limitations (specifically, the inability to determine causality) as well as the likely bidirectionality of infant-caregiver interaction. At one extreme, it could be that heightened caregiver sensitivity is simply a non-causal indicator of another variable or variables that predict better cognitive outcomes among children with ASD. For example, it could be that *HR-ASD* children who go on to have higher ELC scores also have other early social skills during infancy that promote caregivers' sensitive responding to their vocalizations, and that these skills alone are intrinsically related to later outcomes. This possibility in its extreme form is unlikely, given prior experimental work causally connecting contingent sensitive responding to early learning and communicative skills (Goldstein et al., 2010; Miller & Gros-Louis, 2013). However, it is indeed likely that there is a bidirectional feedback loop between infants' behaviours and caregivers' responses, such that *HR-ASD* infants who receive higher sensitivity from caregivers are also promoting increased sensitivity via their own actions. Whilst infants' vocal directedness and sustained attention abilities did not predict increased sensitivity among caregivers in this group (see *Post-hoc* analyses above), other vocal variables, such as the acoustic quality and maturity of infants' vocalizations, may be shown to predict increases in contingent sensitive responding if further analysed (Albert, Schwade, & Goldstein, 2017). In turn, increases in sensitive responding may promote early learning of the associations between objects and the labels/actions that they correspond to (Goldstein &

Schwade, 2009; Goldstein et al., 2010), allowing for enhanced language development as well as enhanced knowledge of the physical and categorical affordances present in infants' broader environments. Future experimental and observation studies among at-risk infants should explore these possibilities.

Alongside the issue of causality in the current study (and the potential benefit of assessing infants' vocal acoustic characteristics in future analyses), other limitations and suggestions for further research should be noted. First, though no differences in infants' attention and vocal behaviours and caregiver responsiveness were observed between our at-risk subgroups (*HR-TD*, *HR-Atyp*, and *HR-ASD*) at 6-10 months, we did not directly compare the behaviours observed in our at-risk groups to behaviours within a low-risk (no familial risk of ASD) sample. Given reports on the Broader Autism Phenotype (BAP), a phenomenon in which undiagnosed family members of those with ASD also show a higher incidence of sub-clinical ASD traits (Losh, Childress, Lam, & Piven, 2008), such a comparison will be critical if we are to further explore potential behavioural differences in social attention and interaction among at-risk infants and caregivers during this period of development. In addition, though our subgroups did not differ *behaviourally* in their social attention and caregiver response patterns, the common behaviours that each subgroup exhibited may have been realised through different cognitive or neural mechanisms (Karmiloff-Smith, 1998; Elsabbagh et al., 2012). To explore this possibility, future studies of at-risk infants' behaviour in natural social contexts should endeavour to include concurrent measures of brain and physiological activity when possible (e.g. Jones, Venema, Lowy, Earl, & Webb, 2015; Liao, Acar, Makeig, & Deak, 2015). Such measures may bring to light differences in neural processes supporting social attention among infants who develop ASD compared to those who do not (e.g. Elsabbagh et al., 2012), and improve our understanding of pathways contributing to ASD at multiple levels of analysis. Finally, though the sample sizes of our outcome subgroups are comparable to those of previous reports (Baker et al., 2010; Northrup & Iverson, 2015; Wan et al., 2013; Wass et al., 2015), further replication of our findings would be ideal, particularly in larger samples.

With the above limitations in mind, our findings provide novel insights into the naturally-occurring dynamics of early parent-infant interaction among infants at risk for ASD in two primary ways. First, ours is one of the first studies to document at-risk infants' moment-by-moment looking preferences and visual responsiveness to social cues in a relatively unstructured free-play environment. In doing so, we have observed how at-risk infants' attention manifests in everyday social contexts, which is an essential step in beginning to understand real-world mechanisms of social development and differences in ASD. Secondly, our work adds to an emerging body of literature characterising caregiver responsiveness and dyadic interaction in ASD. As many studies have either assessed the micro-level timing (contingency, synchrony) or macro-level content of parents' behaviours towards infants and children at risk (Baker et al., 2010; Northrup & Iverson, 2015; Wan et al., 2013; Warlaumont et al., 2014; Yirmiya et al., 2006), our study uses a micro-level approach to identify both the timing *and* content of caregivers' responsiveness to infants, incorporating infants' own visual attention and vocalizations into our analyses of parent behaviour. Our finding that infants' learning outcomes are influenced specifically by caregivers' contingent sensitive responding to vocalizations provides a more tangible and testable understanding of how caregivers may proximally influence learning in infants who develop ASD. We hope that this finding may serve as a springboard for new experiments testing the effectiveness of contingent sensitive responding for enhancing cognitive outcomes among infants and children who develop ASD, and for encouraging further research into mechanisms of communicative and social development in these children.

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SUPPLEMENTAL TABLE S3.1.
Correlations Between Infant Vocal and Social Attention Behaviours, Caregiver Sensitivity, and Scores on the Mullen Scales of Early Learning in *High Risk-ASD* Infants

| ***Measure*** | ***1*** | ***2*** | ***3*** | ***4*** | ***5*** |
|---|---|---|---|---|---|
| **1. Infant proportion of ODVs** | --- | .38 | .03 | -.16 | .19 |
| **2. Infant ODVs per minute** | | --- | -.03 | -.23 | -.31 |
| **3. Infant SA following sensitive response** | | | --- | .44 | .07 |
| **4. Caregiver sensitivity to vocalizations** | | | | --- | .67* |
| **5. Mullen ELC scores at 36 months** | | | | | --- |

*Note*. ODV= Object-directed vocalization; SA= sustained attention (look duration measured in seconds); ELC= Early Learning Composite standard score from the Mullen Scales of Early Learning.
*p<.05

SUPPLEMENTAL TABLE S3.2.
Correlations Between Infant Vocal and Social Attention Behaviours, Caregiver Sensitivity, and Scores on the Mullen Scales of Early Learning across all High-Risk Infants

| ***Measure*** | ***1*** | ***2*** | ***3*** | ***4*** | ***5*** |
|---|---|---|---|---|---|
| **1. Infant proportion of ODVs** | --- | .45** | .14 | -.22 | .07 |
| **2. Infant ODVs per minute** | | --- | -.16 | .04 | -.17 |
| **3. Infant SA following sensitive response** | | | --- | -.02 | .05 |
| **4. Caregiver sensitivity to vocalizations** | | | | --- | .23 |
| **5. Mullen ELC scores at 36 months** | | | | | --- |

*Note*. ODV= Object-directed vocalization; SA= sustained attention (look duration measured in seconds); ELC= Early Learning Composite standard score from the Mullen Scales of Early Learning.
*p<.05; **p<.01

# SYNTHESIS AND DISCUSSION

In this thesis, we began with questions of how early visual attention in humans manifests in natural social contexts, and also of how differences in micro-level aspects of adult-infant social coordination may contribute to individual differences in early looking and learning. To gain further insights into these questions, we first conducted a study of naturalistic observation (Study 1), in which we drew connections between the content of caregivers' contingent social feedback during parent-infant play and infants' concurrent social looking patterns. We then experimentally tested how controlled variations in adults' response frequency and content causally influence real-time changes in infants' social looking, and additionally examined whether adults' response variations (and the moment-by-moment infant looking changes produced by them) predicted behavioral measures of infant arousal in a subsequent neuropsychological vigilance task (Study 2). Finally, we applied our analyses of infant looking and adult responsiveness to a longitudinal sample of parent-infant dyads at high familial risk of autism (ASD), to assess how early patterns of social interaction and infant attentional behavior might predict later learning and social-cognitive outcomes among those at risk (Study 3). Below, I briefly summarize our findings from each study, and describe how they may contribute to our broader understanding of the bidirectional social mechanisms underlying early attention organization in human infancy.

## Summaries of Chapters, Limitations, and Current Directions

One of the primary themes tying together the studies encompassed in this work is the concept of social coordination, whereby participating members of a social interaction show temporal, spatial, and/or semantic alignment in their communicative behavior toward one another. With respect to the adult-infant dyad, we defined adult social coordination in terms of whether adults' behaviors were aligned reliably in time with (i.e., contingent to) infants' looks and prelinguistic vocalizations, as well as whether their behaviors were aligned in space/content with (i.e., sensitive to) the area or object of focus that infants were visually oriented to. Within Study 1 however, we also touched upon (though perhaps more subtly) the reciprocal ways in which infants may exhibit and contribute to social coordination within the dyad as well. One of these ways has been previously described in other early communicative contexts as social selectivity or attunement (Kuchirko, Tafuro, & LeMonda, 2018), in which infants are able to differentiate and respond distinctively to caregiver behaviors that vary in form or content. In study 1, we found that infants whose caregivers showed high ratios of redirective responding (attempts to shift focus) showed increased gaze shifting to caregivers' other (non-referential) behaviors, in addition to showing increased shifting to caregivers' behaviors overall relative to infants of caregivers exhibiting high ratios of sensitive responding. In the context of social attunement, this finding suggested to us (though the direction of causality is intangible within this study) that rather than responding differentially to their caregivers' behaviors, infants of highly redirective caregivers had perhaps learned a general association between their caregivers' overall behaviors and a shift in focus. Though we have yet to follow up on this finding experimentally from the vantage point of infant influences, it would be intriguing to examine whether increased gaze shifting in infants also encourages adult social partners to provide more redirective prompts, perhaps as a means of attempting to re-organize or "rein in" infants' attention. If so, such a process would extend the idea of a dyadic social feedback loop (Goldstein & Schwade, 2009; Warlaumont, Richards, Gilkerson, & Oller, 2014) beyond language and speech development, to include visual and social attention development as well.

Along with social selectivity, another means by which infants may inadvertently promote social coordination is through showing early looking preferences for objects that adults are actively engaged with. As previously described (Introduction), recent work in everyday environments suggests that infants within the first year often show robust looking preferences for objects that adults are manually manipulating compared to other possible looking areas during play (Deák, Krasno, Triesch, Lewis, & Sepeta, 2014). Given that adults' eyes are also typically directed to the objects that they are manipulating, current theories also suggest that infants' development of social attention skills such as gaze following may in fact rely on infants' early looking preferences for adults' held objects, as infants may learn through repeated experiences that their adults' gaze is often aligned with sights they prefer attending to (Deák et al., 2014; Deák, Triesch, Krasno, de Barbaro, & Robledo, 2013). In study 1, we found while infants of highly sensitive caregivers showed looking preferences for caregivers' objects analogous to those described in prior literature (Deák et al., 2014), infants of highly redirective caregivers did *not* exhibit a distinct preference for caregivers' objects over other objects. In addition to potentially reducing the associative learning opportunities that infants may require to learn gaze following, how might such a lack of preference to caregivers' engaged objects influence dyadic coordination on a broader level? More specifically, might such patterns of inattention encourage caregivers to attempt to redirect their infants more frequently? These inquiries require additional study, though other experimental work suggesting that different infant behaviors elicit distinct types of social feedback from caregivers (Albert, Schwade, & Goldstein, 2017) imply that such bidirectional influences are at least possible, if not likely.

Thus, while our findings in Study 1 did not offer answers in terms of the causal direction of effects, these findings did provide a strong rationale for Study 2, in which we experimentally manipulated the timing and content of adults' social feedback to infants in order to determine the causal effects of distinct response patterns on infant social attention and arousal. Another factor motivating Study 2 relates to an ongoing discussion in the developmental literature regarding what infant looking patterns might represent in terms of neurobiological and cognitive processes (Aslin, 2007; de Barbaro, Chiba, & Deák, 2011; Malcuit, Pomerleau, & Lamaree, 1988; Schöner & Thelen, 2006). Through Study 2, I helped to forward the notion that infant looking can be described at least partly in terms of arousal systems (Aston-Jones, Rajkowski, & Cohen, 1999; Aston-Jones & Cohen, 2005; de Barbaro et al., 2011), by replicating significant correlations between conceptual behavioral indices of arousal in infants (latencies to orient to salient stimuli, rates and durations of visual fixations, etc.) and fluctuations in looking behavior toward stimuli that other theoretical accounts of looking would have predicted to elicit fairly uniform visual responses during a visual attention task. Alongside this replication, I also explored how prior exposure to variations in experimenter contingency, sensitivity and redirectiveness transiently influenced infants' arousal-based looking behavior in the above attention task, as well as whether contingency and content interacted to influence infants' in-the-moment social looking behavior during the social interaction itself. One intriguing finding from this study was that, at least in interactions between novel social partners, both contingency and content appeared to interact to affect infants' in-the-moment looking behavior, as only infants receiving both highly redirective *and* highly contingent social interactions exhibited a lack of looking preference for social partners' held objects. Such a finding indicates that infants can perhaps rapidly learn the regularities and interactive value of novel adults' social responses, but only if sufficient input (i.e., high levels of responding) is present. In contrast, only social partners' levels of overall responding (contingency) predicted infants' later arousal-based looking patterns, implying perhaps that the content of adults' responding (at least within the range of content variation that we explored here) is not as potent as the general amount and timing of responding in regulating infants' temporally extended arousal levels and behavior. Additionally, we were able to draw some tentative relations between infant looking behaviors observed during play with experimenters (specifically, looking time to unengaged objects) and subsequent arousal behavior on our later attention paradigm, though further exploration with the remainder of our study sample should be conducted to help strengthen and clarify these findings. Regardless, study 2 did provide support for the notion that specific aspects of adults' social behaviors can causally influence infant visual attention organization, both in-the-moment (within the context of social interaction and attention) and on a broader, temporally-extended level.

As Study 2 was designed to elucidate mechanisms of social attention development from the perspective of adults' influences on infants, our final study (Study 3) sought to assess the influence of infant risk status (familial risk of autism via having an older sibling with ASD, as well as later outcome diagnosis) on infants' early social attention in parent-infant play contexts, and whether differences in infant social attention behaviors, as well as individual differences in caregivers' social feedback, related to later ASD and broader social-cognitive learning outcomes. Contrary to our initial expectations, we found that infants' early social looking patterns did not appear to differ between at-risk infants who subsequently developed ASD compared to infants at risk who went on to develop typically or show sub-threshold symptoms. Additionally, the timing and content of caregivers' responses also did not differ between caregivers of at-risk infants who went on to be typically developing, compared to caregivers of infants who later developed sub-threshold behaviors or received a diagnosis of ASD. However, at-risk infants who later developed ASD did appear to be more powerfully affected by the timing and content of their caregivers' responses than other at-risk infants, as children with ASD who had received high proportions of contingent sensitive responding to their vocalizations achieved improved communicative and perceptual/motor learning outcomes relative to children with ASD who received lower proportions of sensitive contingency. In comparison, there was (surprisingly) no clear relations between caregivers' sensitive responding to infants' vocalizations and learning outcomes in at-risk children who did not develop ASD, suggesting that at-risk infants with ASD might be more sensitive to (and/or reliant overall on) social scaffolding and feedback for achieving enhanced neurocognitive outcomes. Across each of the studies presented in my thesis, Study 3 was perhaps the most illuminating in terms of considering mechanisms of influence that may be indirect or imperceptible via in-the-moment behavior, given that infants who developed ASD showed early behavioral attention patterns that were virtually indistinguishable from at-risk infants who did not develop ASD. Similarly, more recent studies of ASD have focused on explaining later differences in social behavior either through paradigms that study infant social attention from multiple levels of analysis (Elsabbagh et al., 2012), or simply by not focusing on early social attention at all (but rather, considering more general developmental mechanisms that may have broad-spanning social and cognitive effects, depending on the sensitive periods during which they are perturbed (Sinha et al., 2014; Thomas et al., 2009; Thomas, Davis, Karmiloff-Smith, Knowland, & Charman, 2016)).

One caveat that we noted within our analyses for study 3 is that we did not include a low-risk comparison group with whom to compare caregivers' responding and infants' behavior. Though such a comparison would not contribute necessarily to the endeavor of differentiating between who (among those at risk for ASD) will develop ASD and who will not, this comparison is critical if we are to identify how early risk status might influence parent responding and infant behavior on a broader level. Additionally, given reports on the broader autism phenotype in family members of individuals with ASD (Losh, Childress, Lam, & Piven, 2008), it may be possible that families at risk regardless of outcome may exhibit more similar social interaction behaviors across one another when compared to social interaction dynamics within low-risk families. As we did collect baseline interaction data for caregivers and infants in study 2 (as well as study 1, though the ages of infants within study 1 are lower than those of infants in studies 2 and 3 and thus comparisons would be more tenuous), we can use these data to make a few tentative comparisons (Figures D1-D2), so as to better understand how infant risk status may broadly influence early social interaction.

First, considering the matter of caregivers' levels of contingent responding, prior work has suggested that caregivers of infants who develop ASD may respond less selectively to infants' vocal behaviors, perhaps as a means of compensating for their infants' reduced production of more advanced vocal behaviors such as canonical babbling (Patten et al., 2014; Warlaumont et al., 2014). From Figures D1a and D1b, we can observe some tentative evidence in line with this prior finding, as caregivers of infants at risk for ASD (Study 3) appear to provide responses to a higher proportion of their infants' vocalizations compared to caregivers of infants with no apparent indications of risk[14] (Study 2). Even when controlling for the effect of multiparity (by definition, parents of infants at risk for ASD necessarily have more than one

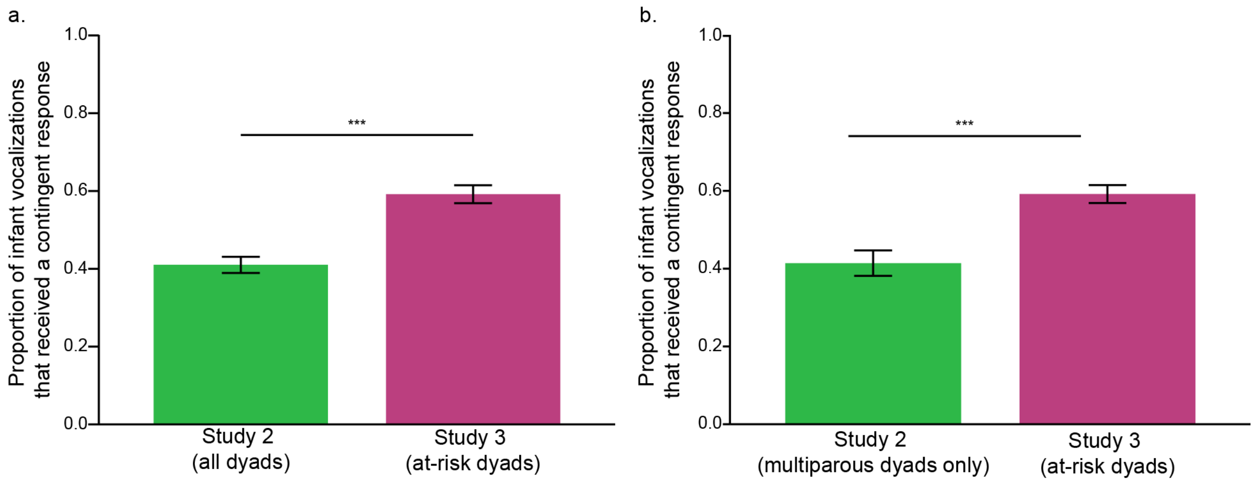


*Figure D1*. Comparison of caregiver contingent responses to vocalizations between studies 2 and 3. a) Illustrates comparisons between all caregivers from study 2 (n=79 codable) and all caregivers from study 3 (n=43 codable), while b) illustrates comparisons between all multiparous caregivers from study 2 (i.e., all caregivers with at least two children (n=31); this is to control for the fact that all parents in study 3 had at least 2 children, as any differences observed within the original comparison may have been otherwise due simply to differences in parity) and all caregivers from study 3 (n=43 codable). ***both ps<.001

child), this difference in level of responding is still significant (Figure D1b; $t(72)= -4.56$, $p<.001$), meaning that differences in parent responding cannot be described simply by a broader effect of having more than one child. While increased contingent responding may seem a positive characteristic on the surface, theories of development in ASD suggest that such non-selective responding to both advanced and immature vocal behaviors may inadvertently detract from communicative learning, as it reduces the potency of the caregivers' social signal for

[14] This statement is tentative, as we have not followed up on these infants to determine whether they went on to receive a neurodevelopmental diagnosis. Additionally, while we did ask parents in Study 2 whether their infant had older siblings, we did not explicitly screen these siblings for the presence of a neurodevelopmental condition (though none of our parents explicitly mentioned having a child with ASD or another condition). With these caveats in mind, our comparisons above are also tentative, and must be replicated in a sample that is explicitly screened for risk status.

reinforcing desirable vocal forms (Warlaumont et al., 2014). While we did not find a correlation between higher levels of responding to vocalizations and children's later learning scores in our sample of children at risk ($r$= .09, $p$=.53), it may be possible that future or more specific learning rates may be affected by such heightened patterns of response. Future work will need to evaluate this possibility more closely.

Regarding the *content* of parents' responding (Figure D2), response content also appears to differ between dyads in studies 2 and 3, as parents of infants at high risk for ASD appear to provide more sensitive responses and less non-referential responses to infants' vocalizations relative to multiparous parents of infants in Study 2. When assessed via a 2 (Study sample) x 2 (Response type: Sensitive vs. Non-referential responses) ANOVA, these differences are also significant (Main model: Study Sample x Response Type interaction: $F(1,71)= 20.89$, $p<.001$; follow-up tests of sensitive responding, Study 2 vs. Study 3 caregivers: $F(1,71)= 21.84$, $p<.001$; non-referential responding, Study 2 vs. Study 3 caregivers: $F(1,71)= 11.07$, $p=.001$). Considering the implications of these differences, it may be possible that caregivers of infants at risk are providing more sensitive responses also as a means of compensation somehow, or perhaps even as a byproduct of increased attention to the child's behaviors and focus as a result of knowing their children's increased risk status. Given that higher proportions of sensitive responding to vocalizations were associated with better learning outcomes in infants who developed ASD in our sample, this increase in sensitivity among our at-risk group is a rather hopeful and auspicious finding, compared to prior studies indicating that signs of early atypicality or impairment may reciprocally encourage responding that reinforces less optimal outcomes (e.g. see Locke, 2001 for discussion of this point). Such increased sensitivity may also assist in countering the possible undesirable effects of generally higher rates of contingent responding discussed previously

(Warlaumont et al., 2014), as parents' contingent responses (if composed mainly of sensitive feedback) would more frequently provide focused information that is relevant to infants' state, even if less discriminatively reinforcing. In view of our speculations, it will be of interest in

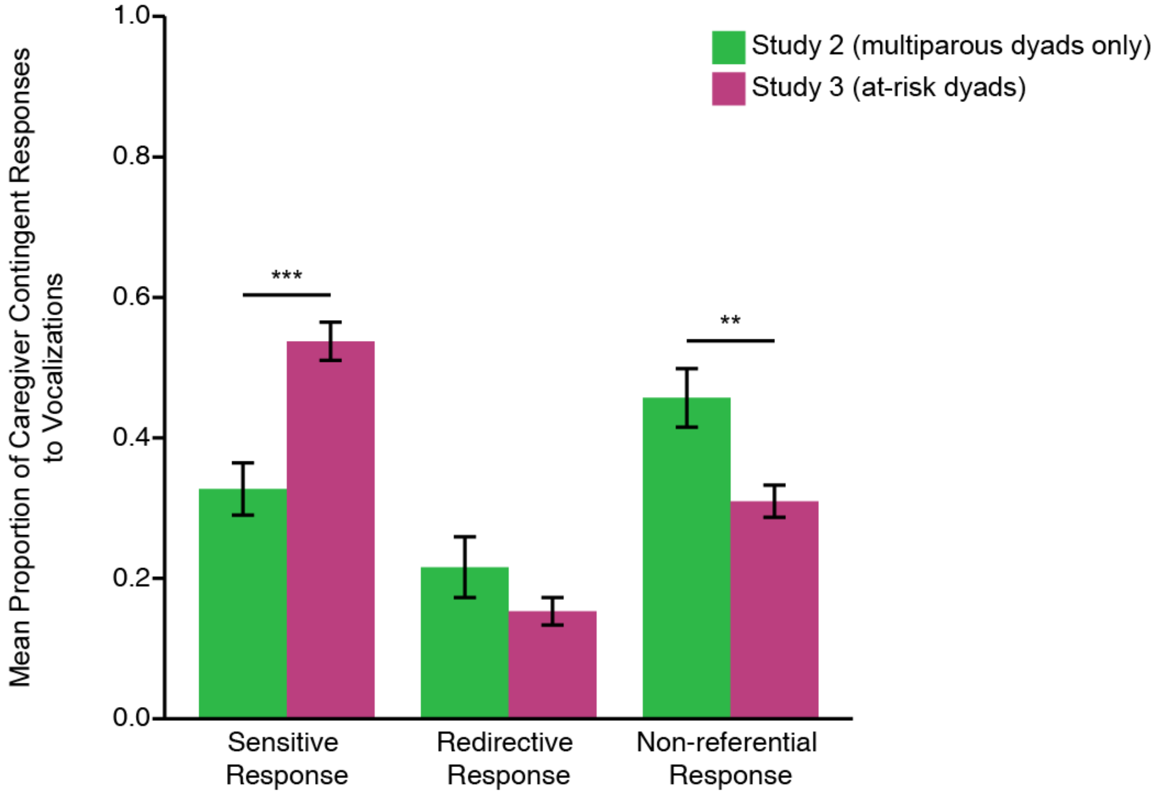


*Figure D2*. Comparison of *content* of caregiver contingent responses to vocalizations between dyads in study 2 (multiparous only) and dyads from study 3. Caregivers of at-risk infants (study 3) produced a greater proportion of sensitive responses than caregivers of infants in study 2, and caregivers of infants in study 2 produced a greater proportion of non-referential responses than caregivers of at-risk dyads. **p<.01; ***p<.001.

future work with infants at risk to tease apart experimentally the relative effects of contingency and content (perhaps in a paradigm similar to Study 2) on children's learning.

Of course, one obvious limitation of the above comparison is that the dyads being compared in studies 2 and 3 also come from different cultural backgrounds (i.e., the United States (U.S.) and the United Kingdom (U.K.) respectively). Though the United States and the

United Kingdom are arguably comparable in terms of demographic variables such as industrialization and westernization (i.e., see “WEIRD” societies; Henrich, Heine, & Norenzayan, 2010), prior cross-cultural studies of parent-infant interaction have documented specific differences in parent response patterns between dyads from the U.S. and from other countries, even when relatively matched on other demographic (i.e., economic and educational) factors (e.g. Bornstein et al., 1992). More specifically, caregivers in the U.S. have been shown in some comparisons to focus more on providing information and labels relevant to stimuli in infants’ external environments (objects, observable events, etc.; Tamis-LeMonda, Bornstein, Cyphers, Toda, & Ogino, 1992), which, in our operational definitions, would likely translate into higher rates of sensitive and/or redirective responding. It is not currently known how caregivers of low-risk infants in the United Kingdom would compare in terms of contingency and content to caregivers of low-risk infants in the U.S., which makes our comparison above particularly tenuous. Nonetheless, the fact that at-risk dyads from the U.K. showed higher proportions stimulus-relevant (i.e., sensitive) responding compared to low-risk dyads from the U.S. (in spite of prior studies indicating a focus on environment-relevant labeling among caregivers in the U.S.) is an intriguing preliminary finding, arguably enough so to merit appropriate follow-up comparisons that include low-risk dyads from the United Kingdom. In general however, a lack of cross-cultural data comparing early dyadic coordination among different societies is a limitation of each of the studies that I have presented above, and future research should work to determine whether individual differences in parent and infant behaviors analogous to those I have examined through my studies are present across different cultures (e.g. Bornstein, Putnick, Cote, Haynes, & Suwalsky, 2015). If so, further work could also examine whether such differences correspond to differences in infant social learning and later attentional outcomes, as well as how caregivers' behaviors may change according to the feedback they receive from their infants.

## Concluding Remarks

Overall, the findings encompassed in my thesis illuminate not only how early social attention manifests in complex naturalistic contexts within both typical and atypical development, but also how individual differences in social coordination between members of the adult-infant dyad relate both observationally and experimentally to differences in early social attention behaviors and later learning outcomes. While our inquiries as scientists are never fully complete, it is my hope that the present work assists in clarifying our hypotheses regarding the relative contributions of contingency and content in influencing infants' social attentional behavior, and also in inspiring further investigations into how infants' reciprocal reactions to caregivers' responses may help to constrain and shape their own attentional and learning environments.

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