EARLY MOTHER-INFANT COORDINATION AND LATER LANGUAGE DEVELOPMENT IN INFANTS AT HIGH AND LOW RISK FOR AUTISM SPECTRUM DISORDER

by

Jessie Bolz Northrup

B.A. in Psychology & Anthropology, Cornell University, 2008

M.S. in Psychology, University of Pittsburgh, 2013

Submitted to the Graduate Faculty of the

Dietrich School of Arts and Sciences in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy

University of Pittsburgh

2018

UNIVERSITY OF PITTSBURGH

DIETRICH SCHOOL OF ARTS AND SCIENCES

This dissertation was presented

by

Jessie Bolz Northrup

It was defended on

September 15, 2017

and approved by

Celia Brownell, Professor, Department of Psychology

Susan B. Campbell, Professor, Department of Psychology

Daniel S. Shaw, Professor, Department of Psychology

Carla Mazefsky, Associate Professor, Department of Psychiatry

Dissertation Advisor: Jana M. Iverson, Professor, Department of Psychology

EARLY MOTHER-INFANT COORDINATION AND LATER LANGUAGE DEVELOPMENT IN INFANTS AT HIGH AND LOW RISK FOR AUTISM SPECTRUM DISORDER

Jessie Northrup, PhD

University of Pittsburgh, 2018

The overarching goal of this research was to describe the development of the dyadic coordination of vocalization and gaze behavior between mothers and infants over the first year of life in infants at heightened vs. low risk for autism spectrum disorder. In addition to describing developmental trajectories of behavior, the study aimed to increase our understanding of how coordination is established and develops by investigating how measures of individual vocal and gaze behavior and their coordination within and across modalities related to one another concurrently and across time, and by relating early interactive behaviors to later language development.

Thirty dyads were recorded playing together with a standard set of toys when infants were 3, 6, 9, and 12 months of age, and mother and infant vocalization and gaze behaviors were coded from these videos on a moment-to-moment basis. Coordination was analyzed using both cross-recurrence quantitative analysis and event-based measures of analysis. Hierarchical linear modeling was used to examine developmental trajectories of vocalization and gaze coordination as well as the multi-modal coordination of these two behaviors.

Results indicated that coordination of the timing of vocalization and gaze behaviors is early emerging and supported by both mother and infant behavior, but that relations between coordination across domains and ages are not straightforward. Furthermore, contrary to expectations, few risk status differences were found, and there was no evidence that early coordination predicted later language development. Taken together, these findings paint a complex picture of how dyadic gaze and vocal coordination develop. Rather than coordination emerging due to individual characteristics of mothers and infants within dyads, the data suggest that coordination emerges as a feature of the larger interaction between infant developmental ability and behavior, mother behavior, and the overarching context of the interaction. The results underscore the importance of understanding mother and infant behavior during social interactions as transactional and multi-modal, and also provide new evidence that coordination of behaviors does not develop in a simple, linear fashion, nor is it driven primarily by parent and infant traits.

TABLE OF CONTENTS

PREFACE .... **XII**

1.0 INTRODUCTION **1**

1.1 COORDINATION OF VOCALIZATIONS AND GAZE IN TYPICAL DEVELOPMENT **4**

1.1.1 Dyadic coordination of vocalizations **4**

1.1.2 Dyadic coordination of gaze **8**

1.1.3 Coordination of gaze and vocalizations **12**

1.2 COMMUNICATIVE COORDINATION IN CAREGIVER-INFANT INTERACTIONS WITH HIGH RISK INFANT SIBLINGS **14**

1.3 THE PRESENT STUDY **19**

2.0 METHODS **26**

2.1 PARTICIPANTS **26**

2.2 PROCEDURE **27**

2.3 CODING **28**

2.3.1 Gaze. **29**

2.3.2 Vocalizations. **29**

2.3.3 Directed Vocalizations. **30**

2.3.4 Reliability. **30**

2.4 OUTCOME MEASURES **31**

2.4.1 Mullen Scales of Early Learning (MSEL; Mullen, 1995) **31**

2.4.2 MacArthur-Bates Communication Development Inventory (CDI; Fenson et al., 1993). ... 32
2.5 DATA REDUCTION ... 32
2.5.1 Cross-recurrence measures of coordination. ... 33
2.5.2 Event measures of coordination. ... 37
2.5.3 Randomized baselines ... 41
2.5.4 Composite Variables ... 41
2.6 DATA ANALYSIS ... 42
3.0 RESULTS ... 45
3.1 INDIVIDUAL VOCAL AND GAZE BEHAVIORS ... 46
3.2 DEVELOPMENT OF VOCALIZATION AND GAZE COORDINATION 54
3.2.1 Vocal Coordination. ... 54
3.2.1.1 Simultaneous Speech. ... 56
3.2.1.2 Infant leading/mother following. ... 58
3.2.1.3 Mother leading/infant following. ... 58
3.2.1.4 Latency to Respond Coordination. ... 58
3.2.1.5 Relations among Vocal Coordination Variables. ... 59
3.2.1.6 Relations between Vocal Coordination Composite and Individual Behaviors. ... 61
3.2.2 Gaze Coordination. ... 62
3.2.2.1 Simultaneous Attention to Faces. ... 64
3.2.2.2 Simultaneous Attention to Objects ... 70
3.3 MULTI-MODAL COORDINATION ... 77

3.3.1 Gaze to Faces. 79
3.3.2 Gaze to Objects. 81
3.4 CONCURRENT RELATIONS AMONG COORDINATION VARIABLES 82
3.5 LONGITUDINAL RELATIONS AMONG COORDINATION VARIABLES 83
3.6 EARLY COORDINATION OF GAZE AND VOCALIZATIONS PREDICTING LATER LANGUAGE 84
4.0 DISCUSSION 86
4.1 THE DEVELOPMENT OF VOCAL AND GAZE COORDINATION IN MOTHER-INFANT DYADS 87
4.2 LACK OF RISK STATUS DIFFERENCES 91
4.3 LACK OF RELATIONS TO LATER LANGUAGE 93
4.4 MOTHER-INFANT COORDINATION IS BIDIRECTIONAL AND MULTI-MODAL 96
4.5 COORDINATION AS A FEATURE OF THE EMERGING DEVELOPMENTAL CONTEXT 99
4.6 GENERAL CONCLUSIONS AND DIRECTIONS FOR FUTURE RESEARCH 104
APPENDIX A 107
APPENDIX B 113
BIBLIOGRAPHY 115

LIST OF TABLES

Table 1. Demographic Information for LR and HR Infants 27

Table 2. Event Measures of Coordination 40

Table 3. Means and Standards Deviations for Vocalization Production 47

Table 4. HLM Models for Vocalization Production 49

Table 5. Means and Standard Deviations for Gaze Behavior 52

Table 6. HLM Models for Gaze Behavior 53

Table 7. Means and Standard Deviations for Vocal Coordination Measures 55

Table 8. HLM Models for Vocal Coordination Measures 57

Table 9. Relations Between Vocal Coordination Variables 60

Table 10. Relations between Vocal Coordination Variables and Individual Vocal Behaviors 62

Table 11. Means and Standard Deviations for Mutual Gaze Coordination 65

Table 12. HLM Models for Mutual Gaze Coordination 66

Table 13. Relations between Mutual Gaze Coordination Variables 69

Table 14. Relations between Mutual Gaze Coordination Composite and Individual Gaze Behaviors 70

Table 15. Means and Standard Deviations for Object Gaze Coordination Variables 71

Table 16. HLM Models of Object Gaze Coordination Variables 72

Table 17. Relations between Object Coordination Variables 75

Table 18. Relations between Object Gaze Coordination Composite and Individual Gaze Behaviors 77

Table 19. Means and Standard Deviations for Multi-Modal Vocalization and Gaze Coordination 78

Table 20. HLM Models of Multi-Modal Vocalization and Gaze Coordination 79

Table 21. Concurrent Relations among Coordination Variables 82

Table 22. Longitudinal Relations among Coordination Variables 84

LIST OF FIGURES

Figure 1. Example raw gaze data stream. 34

Figure 2. Example recurrent plot 34

Figure 3. Example cross-recurrence lag profile. 35

Figure 4. Adjusted Mean Recurrence Plots for Simultaneous Attention to Faces at 3, 6, 9, and 12 months 63

Figure 5. Adjusted Mean Recurrence Plots for Simultaneous Attention to Objects at 3, 6, 9, and 12 months 63

PREFACE

Funding for this research was provided by a National Research Service Award (F31 DC014614) from the National Institute of Deafness and Communication Disorders awarded to Jessie B. Northrup, and further supported by the following grants: NICHD R01 HD079254, UL1 RR024153, and UL1TR000005 awarded to Jana M. Iverson and an Autism Science Foundation Pre-Doctoral Fellowship to Jessie B. Northrup. This work (and my graduate career) would have been impossible without the support, guidance, and encouragement of my advisor, Jana M. Iverson, who always pushed me to be an independent thinker and believed in me even when I doubted myself. I am eternally grateful to the entire Infant Communication Lab team, including the dedicated, hard-working, caring, and extremely generous staff (Krista Pugliesi, Maura Hilser, Shelby Parson, Amy Tavares, Julija Hetherington), the extremely bright and patient undergraduate coders who painstakingly micro-coded hours of mother-infant interactions for this project (Christen Kraemer, Tess Fulcher, Sarah Markert, Hannah Denis, Tara Sciortino, Lissy Petrozza, Rebecca Lopez, Maggie Laird, Sydney Tan, Claire Mesko, Shannon Wetzel, Charissa Garner), and my insightful, brilliant, and ever-supportive graduate student colleagues and friends (Nina Leezenbaum, Kelsey West, Emily Roemer) who made my graduate school experience not just bearable but exciting and inspiring, and who supported me through the roughest patches.

I'd like to additionally thank the members of my dissertation committee for their insightful comments and suggestions on this project, as well as Dr. Chen Yu, who was instrumental in teaching me new data analytic techniques essential to this research. I'd also like to extend my gratitude to the families who dedicated their time to participate in this project and all of the infant

communication lab research projects. It was no small undertaking (and no small time commitment) to open their homes and their lives to our research team over the course of three years (and even longer in some cases!), and I hold these families in the highest regard for their commitment, patience, and generosity.

Finally, I'd like to thank my amazing support system of family and friends who have encouraged and supported me, and perhaps more importantly, helped me maintain balance and perspective, over the many (many) years I've been in school. A special thank you to my incredible husband, Mark Patterson, who not only saw me through every anxiety, disappointment, frustration, celebration, and accomplishment along the way, but who also happily taught me how to code in R and spent hours discussing data analysis with me over dinner. Mark, I am so lucky to have you!

1.0 INTRODUCTION

Parent-infant social interactions play a crucial role in early development. In the first months of life, parents organize behavior toward their infants in contingent ways that facilitate the development of coordinated interactions; and by the time infants are 2-3 months old, these interactions begin to show a coordinated, bidirectional structure across behavioral modalities. Dyadic coordination of the timing of communicative behaviors, such as vocalizations and gaze, establishes structure within what is otherwise a complex, multi-modal, multifaceted interaction. This structure creates predictability, allowing both members of the dyad to anticipate and respond to their partner, and reducing the cognitive load of doing so. As infants improve in their ability to perceive regularities and recognize relationships between their own behavior and changes in their partner's behavior (i.e. social contingencies), coordinated communicative interactions provide opportunities for learning and development (Feldman, 2007; Jaffe et al., 2001; Tarabulsy, Tessier, & Kappas, 1996).

One of the most widely studied aspects of early coordination is vocal turn-taking, or the coordination of the timing of speech sounds between mother and infant that is apparent by the time infants are 4 months. Contingent and coordinated vocal interactions between mothers and infants predict development in a number of areas, including language and communication (Jaffe et al., 2001; Tamis-LeMonda, Bornstein, & Baumwell, 2001; Tomasello & Farrar, 1986). The coordination of vocal behaviors, however, does not occur in isolation. The ability to establish shared gaze to aspects of the environment with a partner is another skill that has implications for development in a number of domains. Research that has examined multiple aspects of parent-infant interaction indicates a close connection between parent and infant vocal and gaze behavior. The coordination of vocalizations and gaze in parent-infant interactions has particularly meaningful implications for language and communication development as infant vocalizations and parental vocal responses that occur within periods of coordinated attention may provide optimal moments for word learning (Goldstein, Schwade, Briesch, & Syal, 2010; Masur, 1982).

Importantly, dyadic coordination is inherently transactional, requiring both members of the dyad to: a) behave in ways that facilitate coordination by providing salient and predictable opportunities for partners to respond; and b) be attuned to and able to perceive the structure of their partner's behavior. Therefore, no aspect of coordination can really be considered in isolation. A mother's responsiveness to her infant depends at least in part on the quality and structure of the infant's behavior, and an infant's communicative behaviors develop in the context of these coordinated social interactions. While research provides some evidence for the predictive utility of early caregiver-infant vocal and gaze coordination for later language and communication development, the majority of this research has examined mother and infant behavior as separate dimensions (i.e., looking only at mother responsivity, e.g. Tamis-LeMonda et al., 2001) making it difficult to understand how mother and infant behaviors influence one another across development. This type of understanding is particularly important for the study of at-risk populations, where subtle disruptions in caregiver-infant coordination could have meaningful cascading effects on development.

One such at-risk population is the younger siblings of children with autism spectrum disorder (ASD). ASD is a neurodevelopmental disorder characterized by deficits in social interaction and communication, as well as the presence of restricted and repetitive behaviors (DSM 5; American Psychiatric Association, 2013). The younger siblings of children with ASD have become the subject of a wide range of prospective longitudinal studies due to their heightened risk (HR) for developing the disorder. While these studies were largely developed to identify early markers of ASD specifically, work to date has revealed that even those HR siblings who do not go on to develop ASD follow heterogeneous trajectories of development, ranging from completely typical to significantly delayed (Jones, Gliga, Bedford, Charman, & Johnson, 2014; Ozonoff et al., 2014; Presmanes, Walden, Stone, & Yoder, 2007). In particular, language development among HR siblings is variable, with many infants exhibiting language delays in the second and third year of life (Iverson et al., 2017; Messinger et al., 2013; Parladé & Iverson, 2015). Despite the prevalence of delayed and atypical language development, both among HR siblings who go on to an ASD diagnosis and those who do not, few studies have focused specifically on predicting language outcomes in HR infants and very little is known about the mechanisms that underlie delay and disorder in this population.

Given the significance of caregiver-infant interactions for early language and communication development (Goldstein & Schwade, 2008; Tamis-LeMonda et al., 2001; Topping, Dekhinet, & Zeedyk, 2012), it is surprising that this central developmental context has been understudied in the HR sibling literature. In particular, while several studies have looked for group level differences in infant and/or maternal behavior during interactions, few have focused specifically on *dyadic coordination* of communicative behaviors and/or attempted to predict individual differences in later development from these early interactions. The present study aims to address this gap in the literature by examining coordination of vocalization and gaze behavior during parent-infant toy play interactions across the first year of life in a group of infants at heightened familial risk for ASD and a comparison group of infants no such risk (low risk; LR) for ASD, and by relating early interactive behaviors to later communication and language development. Not only will the study provide new evidence for how the coordination of vocal and gaze behaviors interact and support one another over the first year of life, but it will do so in a developmentally heterogeneous group of infants, allowing us to understand how individual differences early in life relate to individual differences in later outcome.

In the sections below, I review current literature on vocalization and gaze coordination in parent-infant dyads early in life, and on relations between this early coordination and later language and communication development. This will be followed by a review of research relevant to parent-infant vocal and gaze coordination in HR infants.

1.1 COORDINATION OF VOCALIZATIONS AND GAZE IN TYPICAL DEVELOPMENT

1.1.1 Dyadic coordination of vocalizations

Long before children begin to speak, they use vocal sounds to communicate with social partners. In the first months of life, these sounds consist largely of vegetative and reflexive noises (i.e. fussing, crying, grunting). But over the course of the first year, vocalizations become progressively more speech-like as infants begin producing more fully-resonant vocalizations and consonant-vowel (CV) syllables. Research suggests that vocalizations are the most common communicative signal and response in parent-infant interactions from as early as 4 months of age (Van Egeren, Barratt, & Roach, 2001), and like adults, typically developing (TD) infants and their mothers adjust the timing of their vocalizations to coordinate with those of their social partners (Jaffe et al., 2001).

Jaffe and Feldstein (1970) characterized dyadic vocal interactions using a description of conversational states: vocalizations, simultaneous speech, pauses (silences between 2 vocalizations of the same speaker), and switching pauses (silences occurring between 2 speakers). Research on the development of vocal coordination in infancy using these descriptors has shown that mothers and infants coordinate the timing of these conversational states from around 4 months of age, and that this coordination becomes more sophisticated over the first year of life (Beebe, Alson, Jaffe, Feldstein, & Crown, 1988; Jasnow & Feldstein, 1986). For example, while simultaneous speech is quite common when infants are 4 months old (Jaffe et al., 2001), by 9 months of age caregivers and infants display relatively little simultaneous speech in vocal interactions, indicating an emerging tendency to inhibit vocalizations when a partner is speaking and engage primarily in alternating speech (Jasnow & Feldstein, 1986). It is noteworthy that this developmental picture is based on two separate studies with different samples, rather than a repeated-measures assessment. Thus, little is known about individual trajectories of development or how early coordination might relate to or predict later coordination in TD infants.

The switching pause, or the pause that occurs after one speaker stops speaking and before the other speaker begins is another important aspect of vocal coordination. Research on a variety of dyads, from infant-adult to adult-adult, has repeatedly shown that individuals match their switching-pause durations to those of their partners on a global level (i.e., averaged across an entire interaction), as well as on a moment-to-moment basis, becoming more congruent as an interaction continues (Crown, 1991; Jaffe et al., 2001; Jaffe & Feldstein, 1970). Beebe et al. (1988) found that mother-infant dyads are coordinated in the mean duration of their switching pauses (i.e. have similar durations) by the time infants are 4 months of age, and Jasnow and Feldstein (1986) found this same coordination in interactions between 9-month-old infants and their mothers. The latter study used time-series regression analysis to show that the coordination of switching pauses was occurring not only globally—as an average across the entire interaction—but also on a moment-to moment basis mutually influential over the period of the interaction. This early emerging coordination of switching pauses indicates that the temporal structure of conversation seen in adult interactions is apparent even in interactions with prelinguistic infants.

In much of the literature on parent-infant interactions, switching-pause duration is referred to as "response time" or "latency to respond" and focuses primarily on the speed and consistency with which mothers respond to their infants' vocalizations. Vocal responses that occur within a short time frame (typically within 2 seconds, see Van Egeren et al., 2001) of a partner's vocalization are considered "contingent responses" and research indicates that both parents and infants respond contingently to their partner's vocalizations with vocalizations of their own significantly more often than would be expected by chance (Van Egeren et al., 2001).

Not only are mothers quite good at providing prompt responses to infant non-distress vocalizations, but infants are also able to recognize this contingent behavior from a young age (Gros-Louis, West, Goldstein, & King, 2006; Millar & Watson, 1979). For example, 5 month-old infants will exhibit an "extinction burst"—or rapid increase—in vocalizations when confronted by a non-responsive partner during a face-to-face "still-face" episode, suggesting that by this age infants have established expectations about the influence of their own vocalizations on others (Goldstein, Schwade, & Bornstein, 2009). Furthermore, infants are sufficiently sensitive to the individual characteristics of their own caregivers' synchronous behavior that they prefer strangers who match that level of contingency (Bigelow, 1998). The sensitivity of infants to their parent's vocal contingency is further supported by research showing that mothers who are more responsive tend to have infants who are similarly responsive, indicating co-regulated interactional processes from early in life (Van Egeren et al., 2001). These studies provide clear evidence that the timing of caregiver responses is a salient part of the infant's interactive experience and affects the way the infant, in turn, responds to his or her interlocutor.

Together, the research reviewed here supports the idea that mothers and infants coordinate the timing of their vocalizations in such a way that bolsters predictability and the perception of interpersonal contingencies. By inhibiting vocalizations during their partners' speech, timing their responses in relation to partners' vocalizations consistently, and matching partner's response timing, mother-infant dyads engage in a rhythmic interaction characterized by a regular turn-taking structure. Within these structured interactions, infants are provided the opportunity to learn the value of their vocalizations and are likely to develop increasingly more sophisticated ways of communicating. In fact, numerous studies have shown that caregivers' contingent responses to their infants' vocalizations can have both short- and long-term positive effects on infant's development (Goldstein & Schwade, 2008; Jaffe et al., 2001; Tamis-LeMonda et al., 2001). For example, naturalistic maternal responsiveness—the degree to which mothers respond contingently to their infant's vocalizations—is predictive of later language development and achievement of language milestones (Tamis-LeMonda et al., 2001). On a shorter time scale, several studies have established that when partners respond contingently to infants' vocalizations, infants produce more advanced, speech-like sounds with more consonant-vowel (CV) syllables (Bloom, Russell, & Wassenberg, 1987; Goldstein, King, & West, 2003; Goldstein & Schwade, 2008).

Importantly, the relationship between contingent responsiveness and infant language development is complex and bidirectional in nature. The infant's own understanding of and participation in the dyadic process is an equally meaningful contributor to development. The previously mentioned still-face study by Goldstein and Bornstein (2009) showed that the magnitude of a 5-month-old's extinction burst in response to a still-faced experimenter predicted language comprehension at 13 months. Additionally, in unstructured play sessions between 10 8-month olds and their parents, Gros-Louis et al. (2006) found that parents were less likely to respond contingently to an infant's vocalization that contained only vowel sounds than to a vocalization with a consonant-vowel syllable. Thus, as infants develop more speech-like vocal sounds, the input they receive from adults changes, which in turn influences the infant's vocal and language development. This reciprocal process is overlooked in studies that examine parent or infant behavior alone.

In sum, the current research on parent-infant vocal interactions in TD dyads suggests that dyadic coordination of the timing of vocalizations begins early, that parent contingent responsiveness plays a central role in these interactions and in future language development, and that this process is bidirectional in nature. However, the lack of longitudinal studies that examine both parent and infant behavior has made it difficult to fully examine the nature and mechanisms of development in this area. In addition, very few studies have examined how vocal coordination fits into the larger context of communicative behavior occurring in these interactions, and in particular, the visual context.

1.1.2 Dyadic coordination of gaze

Infant visual attention develops rapidly over the first months of life as infants begin spending more of their time in an alert state, develop the ability to orient their attention to and disengage from stimuli in their environment, and begin to coordinate their looking behavior with social partners (Colombo, 2001; Feldman, 2007). At around 3 months of age, TD infants engage in mutual gaze with their mothers approximately 30-50 percent of the time in face-to-face interactions (Fogel, 1977; Harel, Gordon, Geva, & Feldman, 2011; Tronick, Als, & Brazelton, 1980). During this time, caregivers attend to their infant's face nearly constantly during interactions, while young infants engage in cycles of looking to and away from their parents, likely as a method of regulating emotional arousal (Field, 1981; Van Egeren et al., 2001). Over the course of the first year, the time caregivers and infants spend in mutual gaze decreases, and the time spent in shared attention (i.e. simultaneous attention to objects) increases (Feldman, 2007; Yu & Smith, 2013). This developmental shift has particularly important implications for language development, as caregivers often coordinate shared attention with contingent object naming, thus providing opportunities for word learning (Akhtar, Dunham, & Dunham, 1991; Tomasello & Farrar, 1986).

Joint attention, or the ability to coordinate attention with a social partner to objects or events, is considered a critical skill in language development (Moore & Dunham, 2014). Although the ability to initiate shared attention by shifting gaze between an object and a social partner is considered a hallmark developmental achievement in joint attention skill, infants use a number of increasingly sophisticated skills over the course of the first year in order to coordinate gaze with others (Carpenter, Nagell, Tomasello, Butterworth, & Moore, 1998). The ability to follow another's gaze is one such skill that, under particular circumstances, infants are able to do from the first few days of life (Farroni, Massaccesi, Pividori, & Johnson, 2004).

Several studies have shown a relationship between the ability to follow gaze in structured settings and later language development (Brooks & Meltzoff, 2005; Morales, Mundy, Delgado, Yale, Messinger, et al., 2000; Morales, Mundy, Delgado, Yale, Neal, et al., 2000). Morales, Mundy, Delgado, Yale, Messinger, et al. (2000) found that infants' ability to follow their mother's gaze in a structured context at 6 months was related to both expressive and receptive vocabulary at 30 months of age. In addition, a composite measure of gaze following ability from 6-18 months predicted 30-month expressive vocabulary above and beyond parent report of their child's 24-month vocabulary. This indicates that the ability to follow gaze in the first year and a half of life is a unique contributor to language development in the third year. However, the research on early gaze following is almost entirely conducted in the context of structured, laboratory experiments and suggests that this ability is inconsistent and dependent on a number of contextual factors (Corkum & Moore, 1998; Morales, Mundy, Delgado, Yale, Neal, et al., 2000; Senju & Csibra, 2008).

Importantly, there has been almost no research on how infants follow parent gaze in the context of unstructured social interactions, a significantly more complex context than the structured tasks typically used in gaze following research. An exception is a study by Yu and Smith (2013), who examined parent and infant gaze behavior simultaneously in an unstructured interaction in order to understand how these behaviors occur naturally within the dyad. In interactions between 17 12-month-olds and their mothers, dyads spent approximately a third of the interaction looking at the same object. The authors used lag-based cross-recurrence models to analyze synchrony between parent and infant gaze across varying time lags and found that infants and mothers led and followed one another's gaze equally and within a 5 second lag of their partner's gaze. Infants, however, rarely looked to their mothers' faces at this age, suggesting that eye gaze following is likely not the primary method through which infants establish joint attention with their parents.

This finding is consistent with those of Bakeman and Adamson (1986), who examined instances of "coordinated joint engagement", or the coordination of attention with both an object and a partner as signaled by the infant shifting gaze back and forth between the two, in 28 mother-infant dyads from 6 to 18 months of age. While research has shown that infants have the ability to initiate joint attention in the first year (Carpenter et al., 1998), Bakeman and Adamson found that the average amount of time spent in this state did not exceed 5% until 15 months of age. Again, there appears to be a meaningful distinction between what infants can do and what they actually do in their natural contexts that has implications for our understanding of how these types of skills play a role in infant development.

Notably, most of the research cited above examined only infant behavior. How parents coordinate gaze with their infants also appears to play an important role in development. For example, Mendive, Bornstein, and Sebastián (2013) examined parent behavior preceding moments of coordinated joint engagement (i.e. infant coordinates attention to partner and object) in 33 mother-infant dyads, and found that these moments were most likely to occur when mothers followed and reinforced infants' engagement with an object, and were less likely to occur following mothers' introduction of a new object and redirection of infant attention. Furthermore, research suggests that parents who follow their young infant's focus of attention, thus creating moments of shared attention, have infants who go on to have better cognitive and language abilities (Landry, Smith, Miller-Loncar, & Swank, 1997).

While the research on parent behavior provides some evidence that following into infant's attention aids developmental processes, none of these studies considered how infant behaviors may play a role in the relationship between parent behavior and infant development. For example, infants who shift attention more or less frequently than is typical may have parents who are more likely to redirect their attention, and they may also be less likely to initiate joint attention and have more difficulty learning language. In other words, parent behavior could simply be a reflection of infant behavior. Just as in the literature on vocal coordination, the dearth of research simultaneously examining parent and infant gaze behavior limits our ability to understand the bidirectional nature of these processes.

Furthermore, the theoretical relationship between early attentional coordination and later development supposedly occurs through the coordination of vocal interactions during moments of shared attention. Specifically, with increased moments of shared attention, infants are provided with increased opportunities to learn about objects in their environment from their mothers (e.g. naming events in moments of shared attention; Carpenter et al., 1998; Tomasello & Farrar, 1986). However, the majority of the studies cited here did not consider the multi-modal coordination of vocalization and gaze behavior.

1.1.3 Coordination of gaze and vocalizations

Multi-modal coordination, such as the coordination of gaze with vocalizations, can occur both within an individual (individual coordination; e.g. infant gazes at parent while vocalizing) as well as between two individuals (dyadic coordination; e.g. infant gazes to parent and parent vocalizes). Only a few studies have examined the dyadic coordination of gaze and speech in the first year of life. However, those that have provide evidence for the significance of this cross-modal relationship from a young age.

For example, research on contingent responsiveness provides evidence that mothers and infants respond to each other cross-modally. Van Egeren et al. (2001) examined a wide range of communicative signals occurring between 4 month-old infants and their mothers during a naturalistic interaction, including vocalizations and gaze. Vocalizations were the most common communicative signal and the most common and fastest (i.e., shortest latencies) responses for both mothers and infants at this age. But gaze also played an important role in these interactions. Infants were highly likely to respond to mother vocalizations with vocalizations and/or looks, and mothers were highly likely to respond to infant looks with vocalizations and/or object play. Note that the authors of this paper did not include maternal looks as a signal because, at this young age, mothers spend almost the entire interaction looking to the infant.

Notably, the dyadic coordination of vocalizations and gaze is influenced by the within-individual coordination of these communicative behaviors. A study by Gros-Louis, West, and King (2014) examined maternal responses to infant vocalizations during unstructured interactions between 12 mothers and infants when infants were 8 to 14 months of age and found that mothers were proportionally more likely to respond to infants' mother-directed vocalizations (i.e. vocalizations coordinated with gaze to mother) than to infants' vocalizations directed to objects. Furthermore, Hsu, Fogel, and Messinger (2001) studied 13 mother-infant dyads and found that infants produced more speech-like than non-speech like vocalizations when they were gazing at their mothers than when gazing away during face-to-face interactions between 2 and 6 months. Although these studies examined different developmental periods, taken together they suggest an interactive relationship between infant vocal and gaze behavior and parent responses to these behaviors, and provide initial evidence that vocal coordination may be supported by face looking.

This interaction between individual and dyadic coordination of vocalizations and gaze has clear implications for language and communication development. For example, research with older infants suggests that when parents (or experimenters) coordinate their verbal responses with infants' focus of attention, they create optimal moments for word learning (Baldwin, 1991;

Tomasello & Farrar, 1986). A study by Goldstein et al. (2010) provides evidence that infants may use gaze and vocalizations concurrently to signal a readiness to learn about objects in their environment. The authors demonstrated that 12-month-old infants were more likely to learn about the visual features of objects that they directed vocalizations at, and more likely to learn an object-label association when the label was provided immediately after a vocalization directed at the object.

Taken together, the literature just reviewed supports the idea that infant language learning is supported by the structured coordination of parent and infant behaviors, that coordination of vocalization and gaze behavior in early parent-infant interactions is mutually influential, and that studying these behaviors in isolation likely neglects important pathways by which parent-infant interactions influence language and communication development. Understanding how coordination of these behaviors occurs on both micro (moment-to-moment in an interaction) and macro (across the first months of life) timescales can not only help clarify mechanisms of typical development, but can also inform our understanding of atypical developmental trajectories.

1.2 COMMUNICATIVE COORDINATION IN CAREGIVER-INFANT INTERACTIONS WITH HIGH RISK INFANT SIBLINGS

According to recent estimates, approximately 20 percent of HR siblings are expected to develop ASD themselves and an additional 20- 30% will display non-typical development, particularly in language and communication (Hudry et al., 2014; Ozonoff et al., 2014; Ozonoff et al., 2011). While research has identified language and communication delays associated with risk for ASD that emerge in the second year of life, little is known about the processes that may precede and contribute to these delays in the first year. In particular, research specifically focusing on the coordination of communicative behaviors in parent-infant interactions remains sparse. Given the scarcity of research in this area, the review below will focus largely on evidence of differences in HR infant behavior and development that may impact the dyadic coordination of vocalizations and gaze. This will be followed by a discussion of the small literature on parent behavior in interactions with HR infants and dyadic coordination between parents and HR infants.

While much of the research examining infant behavior in the first year of life has found no group differences between HR and LR infants, a few studies have reported subtle variation in HR infants' early vocalization, gaze, and social behavior that could have important implications for parent-infant interactions. For example, in a cross-sectional study of infant pre-speech vocal behavior, Paul, Fuerst, Ramsay, Chawarska, and Klin (2011) found that HR infants as a group produced fewer speech-like vocalizations, a lower percentage of CV syllables, a less diverse consonant inventory, and a larger number of non-speech vocalizations during social interactions than LR infants at 6, 9, and 12 months of age (Ns ranging from 20 to 38). Another study that focused on in-home naturalistic observations of infants found reduced production of communicative non-word vocalizations and words in HR (N = 15) compared to LR (N = 15) siblings at 13 and 18 months (Winder, Wozniak, Parladé, & Iverson, 2013). However, research on early vocal development in HR infants has been variable and not all studies have reported these types of delays. For example, Chenausky, Nelson, and Tager-Flusberg (2017) found that only HR infants with a later ASD diagnosis produced fewer speech-like vocalizations, and that HR-noASD infants did not differ from their LR peers in production of non-speechlike or speechlike vocalizations. Another recent study reported that, during naturalistic in-home full day recordings, 9 month-old HR infants produced a *higher* frequency of vocalizations than their LR peers, a finding that appeared to be driven by a sup-group of highly vocal infants (Swanson et al., 2017). These inconsistent findings are likely a reflection of the considerable heterogeneity within and between samples of HR infants, with many HR infants developing completely typically, and others showing significant delays. Regardless, it is important to understand how individual differences in early vocal production may impact infants' experiences and development.

As noted above, in typical development, mothers tend to respond contingently to their infants' speech-like vocalizations and are also sensitive to the quality of those vocalizations (Gros-Louis et al., 2006; Van Egeren et al., 2001). Thus, differences in the frequency and types of vocalizations produced by young infants could change the dynamics of parent-infant vocal coordination in subtle but important ways. For example, infants who provide their parents with fewer or less salient opportunities for contingent responses will experience fewer contingencies, and may then have greater difficulty learning about the relationship between their own vocalizations and those of their caregiver.

With regard to gaze, several studies have found no differences between HR and LR infants in the first year of life in the overall amount of time spent looking to a social partner during an interaction (Rozga et al., 2011; Yirmiya et al., 2006; Young, Merin, Rogers, & Ozonoff, 2009). However, HR infants appear to differ from their LR peers in the frequency and timing of their gaze *patterns* during interactions by as early as 6 months (Bedford et al., 2012; Ibanez, Messinger, Newell, Lambert, & Sheskin, 2008). Specifically, Ibanez et al. (2008) found that HR infants (N = 17) shifted their gaze to and from their parent's faces less frequently than LR infants (N = 17) in face-to-face interactions. This finding may be particularly meaningful to the study of parent-infant gaze coordination, as coordinating gaze with a partner requires frequent and flexible gaze shifting in response to a partner's behavior.

Research that has examined more global aspects of infant behavior in the context of parent-infant interactions provides further evidence for early differences in HR infant behavior. For example, a study by Wan et al. (2013) reported lower infant "liveliness" (i.e. level of physical activity) during parent-infant interactions at 6 months in HR infants (N = 45) as compared to LR infants (N = 47), suggesting that young HR infants may be less active in interactions at this age. At 12 months, differences in interactive behavior were specific only to the group of HR infants who went on to have an ASD diagnosis (HR-ASD), and no differences were observed between HR No-ASD infants and LR infants. Campbell, Leezenbaum, Mahoney, Day, and Schmidt (2015) found no differences between HR (N = 35) and LR (N = 27) infants in the frequency of socially directed vocalizations in interactions with their mothers at 11 months, but found that differences in a global measure of infant "social reciprocity" at this age predicted individual differences in autism symptoms at 36 months. While these studies provide some evidence that at least a subgroup of HR infants may display behavioral differences in the context of dyadic interactions from a young age, the use of global measures makes it difficult to determine the source of these differences.

Research on caregiver behavior during parent-infant interactions with HR infants is relatively sparse, but the handful of existing studies suggests that mothers of HR infants with and without ASD are equally responsive and sensitive as mothers of LR children (e.g. Campbell et al., 2015; Kasari, Sigman, Mundy, & Yirmiya, 1988; Leezenbaum, Campbell, Butler, & Iverson, 2014). One exception to this is the Wan et al. (2013) study described above, which found lower "nondirectiveness" among mothers of HR infants compared to mothers of LR infants at 6 months. Importantly, however, this study examined maternal behavior as an independent variable, separate from infant behavior. While there is obvious value in examining individual mother or infant behavior (e.g. contingent responsiveness, gaze following, gesture use) during mother-infant interactions, it is difficult to understand these behaviors outside the dyadic relationship.

Only two studies have specifically examined dyadic coordination during parent-infant interactions among HR siblings. Yirmiya et al. (2006) found that at 4 months, HR dyads (N = 21) were less synchronous during periods of infant-led play—as measured by the time-series correlation of phases of caregiver and infant engagement (e.g., avert, object attend, social attend, object play, social play)—than LR dyads (N = 21). In addition, my own research evaluated the relationship between vocal coordination in mother-infant interactions when infants were 9 months old and later language delay in HR infants and a comparison group of LR infants. This study involved moment-by-moment coding of mother and infant vocalizations during naturalistic toy play interactions when infants were 9 months old (N = 35). We found that the degree to which mothers and HR infants were similar in their latencies to respond (i.e. switching pauses) to one another's vocalizations predicted individual differences in language ability in toddlerhood (Northrup & Iverson, 2015). Although this research provided strong initial evidence for disrupted vocal coordination in HR infants who go on to have language delays, it also raised a number of important questions. In particular, why might we see disrupted vocal coordination in these dyads, how early does it begin, and what might be the mechanisms by which it impacts later language?

Given the differences outlined here in vocalization production, gaze patterns, and dyadic interactions, as well as the importance of caregiver-infant coordination and contingency in typical development, there is reason to believe that language and communication difficulties in HR infants may both contribute to and be exacerbated by disruptions in interactive processes important for learning. The ability to coordinate communicative behavior with a partner both facilitates and requires the development of a complex mix of skills, including selective attention, production of effective communicative behaviors, and social engagement. A deficit or delay in any of these areas could affect caregiver-infant interactions in subtle ways, and the ability to employ these skills simultaneously on a moment-to-moment basis in concert with another person is particularly complex. While the majority of research looking for early markers of delay and disorder in HR infants thus far has focused on individual infant behaviors generally observed in stripped-down, laboratory settings, the proposed study will examine the development of the dyadic coordination of vocalizations and gaze in real time in a naturalistic environment. This not only has the potential to reveal more subtle early markers of delay, but also to provide an understanding of how delays might emerge over time.

1.3 THE PRESENT STUDY

This is the first study to micro-analyze parent and infant vocalization and gaze behavior simultaneously during naturalistic play interactions, and to do so longitudinally across the first year of life. Thus, this research will provide important new insights into typical development. In addition, it also includes a group of infants at heightened risk for communication and language delays in order to examine whether and how early social coordination plays a role in language development. As detailed in the literature review above, previous work has focused primarily on individual infant or caregiver behaviors and/or on one communicative modality at a time (and often at only one age point). Thus, the primary contribution of this project is the longitudinal examination of dyadic and multi-modal coordination, allowing us not only the opportunity to examine change in coordination over time, but also to understand how mother and infant behavior relate to one another and how vocalization and gaze behaviors interact and support coordination in these domains. The study has seven specific aims:

Aim 1: Describe the development of production and coordination of vocalizations and gaze behavior during toy play interactions between infants and their caregivers over the first year of life (3, 6, 9, and 12 months) in a group of LR infants and their mothers. This will be the first study to our knowledge to look at the *dyadic* coordination of vocalizations and gaze behavior in a longitudinal sample. Based on previous research, we hypothesize that:

1) Coordination of mother and infant vocalizations and coordination of mother and infant gaze to face will be greater than expected by chance at 3 months, while coordination of mother and infant gaze to toys will emerge later in the first year.
2) As infants get older they will become more coordinated with their mothers in vocalization and gaze behaviors.
3) While gaze coordination will be primarily led by mothers (i.e. the recurrence and frequency of mother leading/infant following would be higher than the recurrence and frequency of infant leading/mother following) early in the first year, mothers and infants will become equal partners in leading and following by 12 months of age.

Aim 2: Determine whether production and coordination of vocalizations and gaze differ between dyads with LR infants and dyads with HR infants. Based on previous research, we do not expect to find differences in the production of vocalizations overall, nor in the duration of gazes to social partners or objects. The following risk status differences are hypothesized:

1) HR infants will produce a lower proportion of pre-speech vocalizations and consonant vowel syllables than LR infants (Paul et al., 2011; Winder et al., 2013).
2) HR infants will exhibit less frequent gaze shifts than LR infants (Ibanez et al., 2008).

3) HR infants and their mothers will show slower growth in coordination across all modalities compared to LR infants and their mothers.

Aim 3: Examine the relationship between different measures of vocalization and gaze coordination. One of the strengths of the current study is the use of multiple measures of coordination describing different aspects of the interaction (explained in detail in the Methods section below). This aim has both conceptual and methodological importance. Conceptually, we are interested in the ways that different aspects of coordination (e.g. frequency of simultaneous speech and coordination of latencies to respond) relate to one another. Are these separate dimensions of coordination, or do they all fit into a larger structure of coordinated behavior? Furthermore, as discussed above, few studies have examined both mother and infant behavior simultaneously. Given the inherently bidirectional nature of dyadic coordination, we are interested in exploring how measures of infant following mother relate to measures of mother following infant.

From a methodological standpoint, this will be the first study to combine modern techniques for evaluating coordination (i.e. cross-recurrence quantification analysis, as used by Yu & Smith, 2013 to study gaze coordination and by Waurlamont et al., 2014 to study vocal coordination) with more traditional measures of vocal and gaze coordination (e.g. maternal contingent responses, gaze following), giving us the opportunity to examine the relations between these techniques. We hypothesize that:

1) Within domains (i.e. vocal, gaze), measures of coordination will relate to one another.
    a) Specifically, for vocal coordination, we hypothesize that dyads with higher latency to respond coordination (i.e. mothers and infants have similar mean latencies to respond) will also have less simultaneous speech and a higher

degree of contingent responsiveness. This is consistent with the theory that each of these aspects of vocal coordination work together to create a predictable, rhythmic interaction.

b) For gaze coordination, we hypothesize that mothers and infants who follow one another's gaze faster and more frequently will also have higher recurrence rates (i.e. will spend a greater amount of time in simultaneous attention).

2) We predict that, due to the bidirectional nature of dyadic coordination, measures of mother leading/infant following will be related to measures of infant leading/mother following. In other words, dyads with more coordinated or "responsive" mothers will also have more coordinated or "responsive" infants (Jaffe et al., 2001; Van Egeren et al., 2001).

Aim 4. Examine the relations between coordination variables and individual mother and infant behaviors. Previous research suggests that coordination of vocalizations and gaze is supported by the individual behaviors of infants and mothers both within domains and across domains (Gros-Louis et al., 2006; Gros-Louis et al., 2014; Van Egeren et al., 2001). We will test several specific hypotheses related to how individual mother and infant vocal and gaze behaviors relate to the coordination of vocalizations and gaze.

1) Vocal coordination will be positively related to the frequency of infant vocalizations, proportion of speech-like vocalizations, and proportion of CV vocalizations within age points. Specifically, dyads with infants who vocalize more and with more advanced speech-like vocalizations will be more coordinated with their mothers (Gros-Louis et al., 2006).

2) Proportion of vocalizations directed to partner's face will be predictive of vocal coordination. Mothers and infants who direct more of their vocalizations to one another's faces will also have better vocal coordination (Gros-Louis, West, and King, 2014).
3) Vocal behavior during gaze to face and objects will be related to coordination of gaze. Specifically, rate of vocalizations during object looking will be predictive of dyadic coordination of gaze to objects within age points, and rate of vocalizations directed to partner's face will be predictive of dyadic coordination of gaze to faces (i.e. mutual gaze).
4) We hypothesize that the frequency with which mothers and infants shift their gaze will be related to gaze coordination, however we do not have a specific hypothesis as to the direction of this relationship. On the one hand, it may be that more frequent gaze shifts are indicative of flexibility which would allow for better coordination, on the other hand, longer gaze shifts may make it easier for a partner to coordinate his/her gaze.

Aim 5. Examine the role of vocalizations in gaze coordination. Given the important role of visual attention in the relationship between vocal coordination and language development, we will examine the multi-modal coordination of vocal and gaze behavior by analyzing how mothers and infants time their directed vocalizations (i.e., vocalizations that occur during looks to objects or partner's face) with their partner's gaze behavior. Here, we present two specific questions and predictions regarding the coordination of mother and infant directed vocalizations and gaze:

1) Do mothers and infants follow the direction of their partners' vocalizations with gaze to that location contingently and more than would be expect by chance? How does this change in relation to infant age and risk status?

    a) We hypothesize that mothers will look to the location where their infants direct a vocalization more than would be expect by chance starting at 3 months.

    b) We hypothesize that infants will look to their mothers' faces contingent upon mothers' vocalizations to infants' faces as early as 3 months, but will not follow mother's vocalizations to toys contingently until later in the first year.

2) Do mothers and infants vocalize in the direction their partner is looking contingently and more often than would be expected by chance? How does this change based on infant age and risk status?

    a) We hypothesize that mothers will respond to their infant's gaze shifts with vocalizations in the direction of infant's gaze more than would be expected by chance starting at 3 months.

    b) We hypothesize that infant vocalizations will not be contingent on mother's gaze behavior at 3 months, but will become more coordinated over time.

Aim 6. Examine the relationship among coordination variables within and across time points. We are interested in examining the relationships among coordination variables across modalities, as well as within and across age points. This aim will be largely exploratory, as this is the first study to examine these relationships. This aim will encompass the following specific questions and predictions:

1) What is the relationship between coordination variables across domains at each age?

a. Coordination variables will not be related at 3 months, but by later in the first year, coordination in one modality will predict coordination in other modalities (i.e., dyads that are more coordinated in vocalizations will be more coordinated in gaze behavior).

2) What is the relationship between coordination variables across ages?

a. Within dyads, coordination will show consistency across development. Within domains, coordination at one age will predict coordination at the next age.

b. Early emerging coordination will predict later emerging coordination in other domains. Specifically, coordination of vocalizations at 3 months will predict coordination of gaze at later months.

Aim 7: Examine whether individual differences in production and coordination of verbal and non-verbal communicative behaviors in the first year predict individual differences in language and communication skills in the second year. A number of studies cited above have examined how individual parent or infant behaviors predict later language development. Here, we are interested in determining what measures of early vocalization and gaze behavior are most important for predicting later language development. Thus, the analyses will be largely exploratory. Overall, we expect that the dyadic coordination of vocalization and gaze behavior in the first year will be predictive of language skill in the second year. Specifically, based on the theory and research reviewed above, we hypothesize that vocal coordination and multimodal coordination (i.e. coordination of infant and mother directed vocalizations with partner's gaze) in the second half of the first year will be most predictive of later language.

2.0 METHODS

2.1 PARTICIPANTS

Participants for this study were recruited through a larger longitudinal study of reaching, posture, object exploration, and language in infants at high and low risk (LR; no family history of ASD) for ASD. Beginning in December 2013, all participants entering the larger study were asked if they would like to participate in a study of parent-infant interaction. Nearly all families that were asked agreed to participate (90%).

All infant participants were full-term, from uncomplicated pregnancies and deliveries, free from known genetic syndromes, sensory impairments, and non-febrile seizures, and from English-speaking homes. All HR infants had an older sibling diagnosed with ASD, and all LR infants had no first- or second-degree relatives with ASD and at least one older sibling with no referrals for developmental delays or intervention services. LR infants were recruited from the Magee-Women's Hospital birth registry, local parent-infant programs, and day care centers, and HR infants were recruited via the Pittsburgh Early Autism Study, clinics in the University of Pittsburgh Medical Center system, and support organizations for families of children with Autism.

The present study included 17 LR (12 male) and 13 HR (9 male) infant-mother dyads. Table 1 displays demographic information for infants in both groups. As can be seen in the table, infants were primarily Caucasian and non-Hispanic (83%) and college educated (90%). The sample included 2 African-American (HR), 1 Hispanic (HR), and 3 mixed-race (Caucasian and African-American; all LR) infants. LR mothers and fathers were somewhat younger than HR mothers and fathers (mothers: $t(28) = -2.89$, $p = .007$; fathers: $t(28) = -2.49$, $p = .019$).

Furthermore, LR mothers and fathers were more likely to have received higher education than HR mothers and fathers, although these differences did not reach significance (mothers: X^2 (2, N = 30) = 5.57, p = .062; fathers: X^2 (2, N = 30) = 4.90, p = .086).

Table 1. Demographic Information for LR and HR Infants

	Low Risk (n = 17)		High Risk (n = 13)	
Gender Male (%)	12	(70.6%)	9	(69.2%)
Racial or ethnic minority (%)	3	(17.7%)	2	(15.4%)
Mean age for mothers (SD)	31.76	(3.65)	35.46	(3.23)
Mean age for fathers (SD)	32.41	(3.92)	37.54	(7.24)
Maternal Education				
Graduate of Professional School (%)	7	(41.2%)	2	(15.4%)
Some College of College Degree (%)	10	(58.8%)	8	(61.5%)
High School (%)	0	(0%)	3	(23.1%)
Paternal Education				
Graduate of Professional School (%)	11	(64.7%)	4	(30.8%)
Some College of College Degree (%)	6	(35.3%)	7	(53.8%)
High School (%)	0	(0%	2	(15.4%)

2.2 PROCEDURE

Infants and mothers were observed in their own homes playing with a standard set of toys for 10 minutes at 3, 6, 9, and 12 months of age. Toys were provided by the experimenters (a rattle, stacking rings, a spherical puzzle, and a book), and mothers were simply instructed to play face-to-face with their infants as they normally would. A boppy pillow was also given to the mothers to provide additional postural support to infants if desired.

These 10 minute interactions were video recorded by two hand-held cameras, one focused on the infant and one focused on the mother, in order to better capture the behavior of both members of the dyads. To enhance the quality of the audio component of the videos, infants wore a small wireless microphone clipped to a cloth vest worn over their clothing.

2.3 CODING

A five-minute segment from each 10 minute observation was coded. This five minute segment was chosen based on a two-part process. First, any interruptions (e.g. parent asks experimenter a question, older sibling enters the room) during the 10 minute interaction were noted. Obtaining an uninterrupted segment of observation was important due to our interest in analyzing parent-infant coordination. Interruptions could disrupt coordinated interactions and impact data analyses. Second, the five uninterrupted minutes following the first 2 minutes of interaction were identified. If no interruption occurred, or an interruption occurred only in the first 2 minutes or the last 3 minutes of the interaction, the segment from 2:00-7:00 was used. If an interruption occurred within the 2:00-7:00 segment, the uninterrupted segment closest to the middle of the observation was chosen. The segment closest to the middle of the 10 minute interaction was chosen as it allows for a short warm up period but minimizes fatigue. Coding start times did not differ between risk groups at any age point.

Videotapes were coded by independent observers naive to Risk Status of infants and trained to criterion (achievement of at least 80% reliability on three consecutive clips). All behaviors were coded using a time-locked annotation program (ELAN; Brugman & Russel, 2004) to allow for detailed analyses of the relative timing of mother and infant communicative behaviors. For coding of gaze, video of mother and infant was synchronized and watched simultaneously side-by-side in order to enhance the ability of coders to accurately assess the object of each subject's gaze.

However, for coding of both gaze and vocalization, mother and infant behavior were coded at separate times. Detailed descriptions of the coding systems are presented in Appendix A.

2.3.1 Gaze.

Mother and infant gaze was coded when it was directed at either their partner's face or a toy, and the location of gaze (i.e. to partner vs. to object) was identified. For each instance of gaze directed toward a toy, coders noted which specific object was being looked at. Periods during which mother and infant gaze was not coded were identified as either "undirected" (if mother or infant was looking at something other than their partner's face or one of the toys), or "unclear" (if the angle or quality of the video made this moment impossible to code). "Unclear" codes were rare (Mean for mothers: 3.5 seconds, SD: 5.14; Mean for infants: 2.3 seconds, SD: 3.55), and preliminary analyses indicated no difference between dyads with HR and LR infants in the amount of "unclear" gaze at any age. One mother gaze video could not be coded due to poor quality of the video.

2.3.2 Vocalizations.

Mother and infant gaze was coded when it was directed at either their partner's face or a toy, and the location of gaze (i.e. to partner vs. to object) was identified. For each instance of gaze directed toward a toy, coders noted which specific object was being looked at. Periods during which mother and infant gaze was not coded were identified as either "undirected" (if mother or infant was looking at something other than their partner's face or one of the toys), or "unclear" (if the angle or quality of the video made this moment impossible to code). "Unclear" codes were rare (Mean for mothers: 3.5 seconds, SD: 5.14; Mean for infants: 2.3 seconds, SD: 3.55), and preliminary analyses indicated no difference between dyads with HR and LR infants in the amount of "unclear" gaze at any age. One mother gaze video could not be coded due to poor quality of the video.

2.3.3 Directed Vocalizations.

Due to the time-locked nature of the coding of gaze and vocalizations, these two behavioral streams were combined to determine the location of mother and infant gaze during vocalizations. Two variables describing how mothers and infants coordinated their vocalizations with gaze were created. First, the proportion of vocalizations that were directed at toys, partner's face, or both toys and face (within one vocalization) were determined. A vocalization was considered directed if the individual looked at a toy or their partner's face at any point during the vocalization. Second, the rate of vocalizations per 10 seconds during gaze to toys and during gaze to partner's face were calculate. All vocalizations that began during a look to one of these locations were counted in the rate of vocalizations. The first of these variables provides information on how mothers and infants directed their vocalizations, controlling for the frequency of vocalizations produced overall; the latter variable provides information on how mother's and infant's vocalized dependent on their gaze direction, controlling for the amount of total time they spent looking to face vs. toys.

2.3.4 Reliability.

All coders were trained to 80% reliability on 3 consecutive clips prior to beginning independent coding. Following establishment of reliability, video clips were double coded and discussed regularly in order to prevent coder drift and allow for estimations of reliability. Approximately 18-24% of videos were double coded for each behavior, balancing across age and infant risk status (N = 21/96 infant gaze; N = 18/95 mother gaze; N = 19/96 infant vocalization identification; N = 21/29 mother vocalization identification; N = 23/96 infant vocalization type). For gaze and vocalization identification, reliability was calculated on frame-by-frame coding based on the nature of the data reduction and analysis used in this project (see below). Average Cohen's kappa values were 0.75 for infant gaze, 0.73 for mother gaze, 0.89 for infant vocalizations, and 0.91 for mother vocalizations. Kappa values for categorizing infant vocalizations were .70 for infant vocalization type (linguistic, non-linguistic, affective) and .83 for presence of a consonant.

2.4 OUTCOME MEASURES

2.4.1 **Mullen Scales of Early Learning** (MSEL; Mullen, 1995).

As part of the larger longitudinal study, the MSEL is administered to all HR and LR children at the 18, 24, and 36 month follow-up visits. The MSEL is a normed, standardized developmental assessment of language, cognitive and motor functioning. For the purposes of the current study, the Receptive (RL) and Expressive (EL) Language subscales from the 18 and 24 month visits were utilized. Not all infants in the study had reached their 18 or 24 month birthdays by the time of this paper, and some infants had missing 18 or 24 month visits and/or Mullen administrations. Thus, Mullen scores were available for 20 infants (8 HR) at 18 months, and for 17 infants (7 HR) at 24 months.

2.4.2 **MacArthur-Bates Communication Development Inventory** (CDI; Fenson et al., 1993).

Parents of both HR and LR children complete the CDI at 18, 24, and 36 months. The CDI is a widely used measure of expressive and receptive vocabulary, as well as grammar. It has excellent internal consistency and test-retest reliability, as well as concurrent validity with tester administered measures (Fenson et al., 1993). The Words and Sentences Form of the MacArthur-Bates CDI is designed for use with children 16 to 30 months of age and consists of two parts. Part I is a 680-word vocabulary checklist organized into 22 semantic categories that asks parents to indicate words that their child says. The second section consists of questions relating to children's use of English morphology and syntax. For the purposes of this study the 18 and 24 month "Words Produced" score, generated from the vocabulary checklist of the Words and Sentences Form, was used. CDI scores were available for 22 infants (9 HR) at 18 months and 20 infants (8 HR) at 24 months at the time of this defense.

2.5 DATA REDUCTION

This study was designed to examine the development of coordinated communication in the first year of life in HR and LR infants and their mothers. Data were available for 20 infant-mother dyads at 3 months (2 enrolled in the larger study after 3 months, 2 were already 3 months when the toy play study began recruiting, 1 cried inconsolably after 2 minutes, 5 had missed visits), 25 dyads at 6 months (5 missed visits), 27 dyads at 9 months (2 missed visits, 1 not yet 9 months at time of data analysis), and 24 dyads at 12 months (2 began study before 12 month visit was added, 4 missed visits, 1 not yet 12 months at time of defense).

2.5.1 Cross-recurrence measures of coordination.

Cross-recurrence measures of coordination (e.g. Warlaumont et al., 2010; Yu & Smith, 2013) were used to examine coordination of mother and infant gaze and vocalization behavior on a moment-to-moment basis. In this type of analysis, two categorical temporal data streams are aligned, and their temporal coordination is measured with varying degrees of lag.

As an example, Figure 1 depicts the raw data streams for one mother-infant dyad over a 100 second period. As can be seen in the figure, the raw gaze streams can be used to examine instances of overlap, or simultaneous attention to the same location. Figure 2 displays the recurrent plot for this mother-infant pair. The horizontal dimension represents the infant's gaze data, while the vertical dimension represents the mother's data. The diagonal running from the bottom left corner to the top right corner indicates instances of simultaneous attention to the same location, or coordination at a time lag of zero, with black pixels indicating the mother and infant were gazing at the same place at the same time and white pixels indicating that they were not (thus, in an analysis of vocalization data, this diagonal would represent instances when parent and infant were vocalizing at the same time). Parallel diagonals represent coordination at varying time-lags, with pixels below the diagonal corresponding to instances of parent following infant gaze, and pixels above the diagonal corresponding to infant following parent.

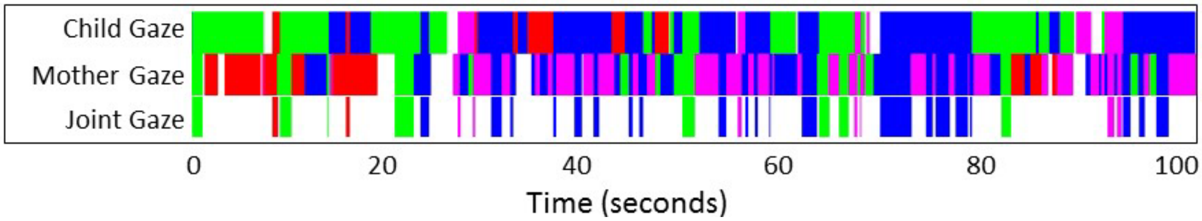


Figure 1. Example raw gaze data stream.

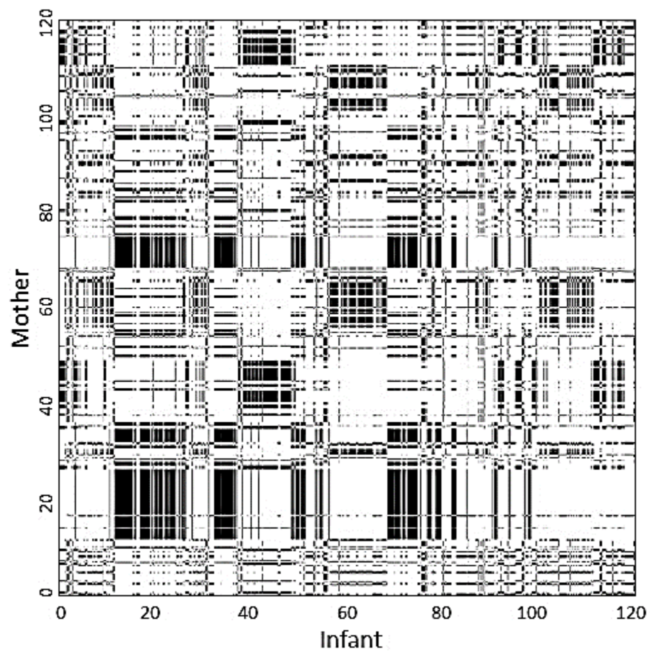


Figure 2. Example recurrent plot

In order to quantify patterns of coordination, cross-recurrence lag profiles are created by: 1) computing the percentage match (total matches/total time series) along the diagonal line representing 0 lag; 2) taking parallel diagonal lines to the primary diagonal line and deriving a percent match for each parallel diagonal (each match indicates how much parent and infant were coordinated at a given time lag). A diagonal-wise recurrence lag profile can then be created reflecting the pattern of coordination between the two data streams at different degrees of lag.

Figure 3 represents the cross-recurrence lag profile for the example dyad. The 0 point along the x-axis indicates gaze to the same location at the same time, while points to the right indicate parent gaze followed infant gaze at each lag, and points on the left indicate infant gaze followed by parent gaze at each lag. Several measures of coordination can then be determined from this profile.

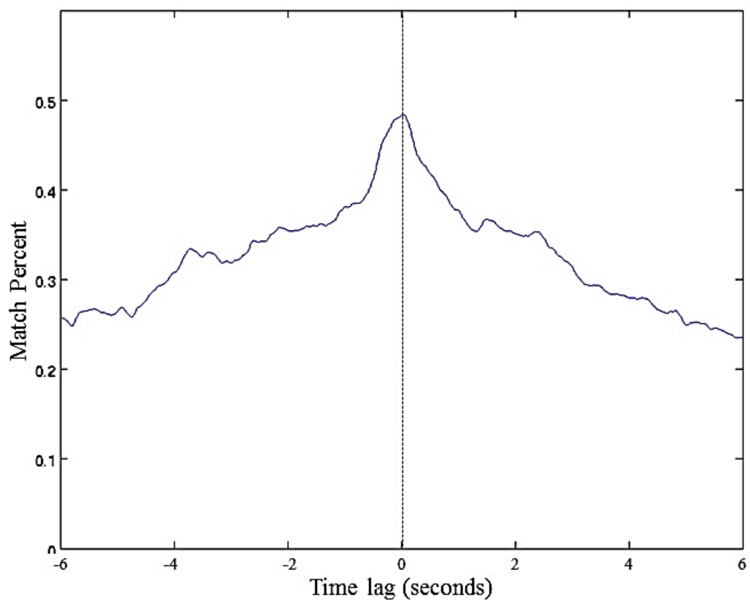


Figure 3. Example cross-recurrence lag profile.

For the purposes of this research, coded data was transformed into 33.33ms bins (30 bins/second) and cross-recurrence measures were calculated at a 5 second lag leading up to and following 0 (Yu and Smith, 2013). The following variables were examined:

- *Vocal Coordination*: Cross-recurrence profiles for vocalizations indicate the degree to which mothers' and infants' vocalizations occurred simultaneously and at varying degrees of lag. In order to examine lagged coordination, we removed instances of simultaneous speech and fixed the duration of all vocalizations to 1 second (while maintaining the exact lag times between vocalizations). This process has the effect of controlling for the duration of vocalizations so that the lagged recurrence measures better reflect the timing between offsets and onsets of infant and adult vocalizations (see Warlaumont, Richards, Gilkerson & Oller, 2014; Abney, Warlaumont, Oller, Wallot & Kello, 2017). All vocal coordination measures (including event based coordination measures described below) were calculated using only non-affective vocalizations. Measures of vocal coordination included:

  - Total simultaneous recurrence of mother and infant vocalizations: recurrence rate at lag 0. A measure of the total amount of time mothers and infants spent vocalizing at the same moment.
  - Max recurrence of *infant leading/mother following*: Maximal recurrence rate to the left of 0. A measure of the maximum lagged match for mother vocalizations occurring after infant vocalizations.
  - Max recurrence of *mother leading/infant following*: Maximal recurrence rate to the right of 0. A measure of the maximum lagged match for infant vocalizations occurring after mother vocalizations.

- *Gaze Coordination:* Cross-recurrence profiles for gaze indicate the degree to which mother and infants attended to the same place at the same time and on varying degrees of lag. These measures were calculated separately for gaze to objects and gaze to faces.
  - Degree to which mother and infant demonstrated *simultaneous attention*: percent match at lag 0. A measure of the total amount of time infants spend in simultaneous attention.
  - Coordination for *infant leading/mother following*: sum of match percent within 5 seconds to left of lag 0. Measure of the degree to which the location mother is

looking matched the location where infant was looking previously at varying degrees of lag up to 5 seconds.

Coordination for *mother leading/infant following*: sum of match percent within 5 seconds to right of lag 0. Measure of the degree to which the location infant is looking matched the location where mother was looking previously at varying degrees of lag up to 5 seconds.

2.5.2 Event measures of coordination.

In addition to cross-recurrence measures of coordination, several event-based measures of coordination were calculated. While cross-recurrence measures provide a broad view of the match between mother and infant both simultaneously and at varying lags, event-based measures provide a clearer sense of the specific leader/follower dynamics in the interactions. Specifically, we will examine the frequency and duration of specific types of dyadic leading-following events were calculated. Table 2 contains definitions and visual depictions of each of these variables.

- Vocal Coordination:
    - *Frequency Contingent Responses*: instances of mother and infant vocalizations followed by a partner's non-overlapping vocalization within 2 seconds of the offset of the original vocalization were counted.
    - *Average Latency to Respond:* the duration of all pauses between the offset of one individual's vocalizations and the onset of their partner's vocalization were calculated and averaged.
    - *Latency to Respond Coordination*: similarity between mother and infant average latencies to respond were calculated by taking the absolute value of the difference

between mother average latency to respond and infant average latency to respond. A score closer to zero indicates more coordination of latency to respond durations.

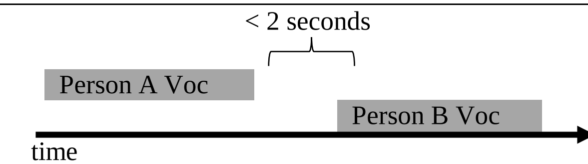
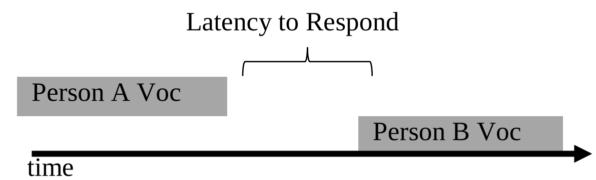
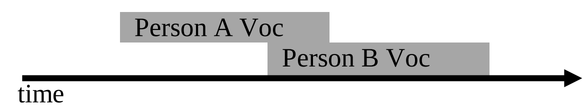
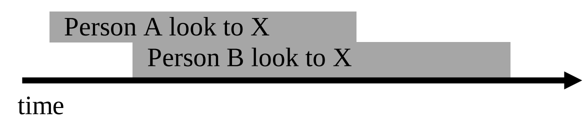
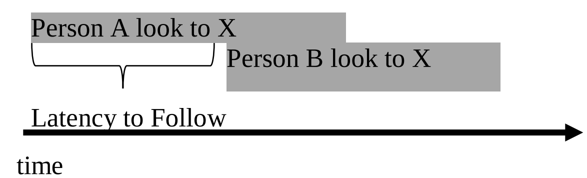
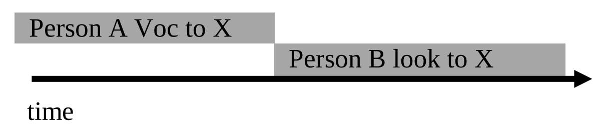
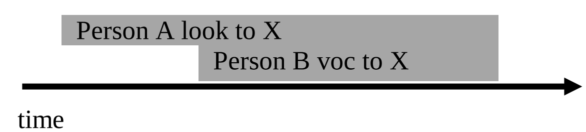
- *Frequency Simultaneous Speech:* instances of mother and infant vocalizations that are "interrupted" by a partner's vocalization were counted. This variable is attributed to the individual who speaks second (for example, *frequency mother simultaneous speech* refers to the number of times the mother begins speaking during an infant's vocalization).

- Gaze Coordination
    - *Frequency and Mean Latency Follows to Simultaneous Attention*: instances when one individual shifted his/her gaze to a location and his/her partner subsequently looked to that same location (thus beginning a moment of simultaneous attention) were counted, and the duration of the lags between the initial person's gaze shift and the beginning of simultaneous attention were calculated and averaged. These variables were calculated separately for simultaneous attention to objects and for simultaneous to faces.
- Coordination of Gaze and Vocalizations: For the purpose of examining multi-modal coordination, each individual's vocalization stream was combined with his/her own gaze stream to create a "directed vocalization" stream. This was then paired with a partner's gaze stream in order to look at the coordination of directed vocalizations and partner's gaze. The following variables were calculated:
    - *Frequency Gaze follows Vocalization:* instances when one individual vocalized to a location (i.e. vocalized while looking to that location) and his/her partner shifted his/her gaze to that location within 5 seconds of the offset of the vocalization were

counted. This variable was calculated separately for vocalizations directed at objects and vocalizations directed at faces.

Frequency Vocal Response to Gaze: instances when one individual shifted his/her gaze to a location and his/her partner subsequently vocalized while looking in that location and before the initial gaze was over (i.e. during a moment of simultaneous attention) were counted. This variable was calculated separately for gaze to objects and gaze to faces.

Table 2. Event Measures of Coordination

Domain	Variable	Definition	
Vocal Coordination	Frequency Contingency Response	Frequency Person B’s Vocalization follows offset of Person A’s within 2 seconds.	
	Mean Latency to Respond	Mean latency between offset of Person A’s vocalization and onset of Person B’s vocalization	
	Latency to Respond Coordination	Absolute value of the difference between Person A’s Mean Latency to Respond and Person B’s Latency to Respond	
	Frequency Simultaneous Speech	Frequency Person B’s vocalization begins during Person A’s Vocalization	
Gaze Coordination	Frequency follow to simultaneous attention	Frequency Person B looks to location Person A is looking (while Person A is still looking there).	
	Mean latency follow to simultaneous attention	Mean latency between when Person A looks to a new location and Person B looks to that same location (while Person A is still looking there).	
Gaze and Vocalization Coordination	Frequency gaze follows vocalization	Frequency person B looks to the location where Person A directed a vocalization within 5 seconds of the offset of the vocalization.	
	Frequency vocalizations follows gaze	Frequency Person B’s vocalization follows Person A’s gaze shift to a new location such that Person B’s vocalization occurs during a moment of simultaneous attention (i.e. before Person A’s gaze to that location ends.	

2.5.3 Randomized baselines

In order to determine whether our measures of coordination exceeded chance levels, randomized baselines were created for each variable of interest in the following way: 1) Each individual's event profile was shuffled randomly 500 times (maintaining the durations and locations of all gaze and vocalization behaviors); 2) Coordination variables were calculated from all 500 shuffled profiles (in the case of cross-recurrence measures of coordination, the shuffled profiles were first turned into 33.33ms binned streams, and then cross-recurrence measures were calculated); 3) For each coordination variable, the mean of all shuffled coordination variables was taken; and 4) The mean shuffled coordination variables were subtracted from the true coordination variables in order to obtain the value of coordination adjusting for chance. If this adjusted coordination is significantly different from zero, then we can conclude coordination has occurred at levels greater than would be expected by chance. For further details on this process, see Appendix B.

2.5.4 Composite Variables

Following examination of developmental trends, risk status differences, and relations between measures (Aims 1 through 3 above), we created composite variables for each behavioral domain (i.e. vocal, gaze). Cronbach's alpha was used to assess how closely related each set of coordination variables were as a group at each age. Scales were considered internally consistent if they had Cronbach's alphas > 0.7. In the case that Cronbach's alphas were less than .7 with all variables included, we removed items that were least related to other measures. This process was continued until an alpha of .7 was reached. Variables that fit together with an alpha of .7 or higher were made into composite variables.

2.6 DATA ANALYSIS

Hierarchical linear modeling (HLM; Raudenbush, 2004; Raudenbush & Bryk, 2002) was used to create and compare growth trajectories for measures of coordination. HLM is an appropriate analytical tool for data consisting of multiple time points nested within individuals and assesses the data at two levels. First, HLM assesses variation *within individuals* over time (i.e. growth trajectories; level 1), and second, it assesses variation *between individuals* in growth trajectories (level 2). HLM can also accommodate missing data, thus all available data can be used without the need for listwise deletion (Huttenlocher, Haight, Bryk, Seltzer, & Lyons, 1991; Willett, Singer, & Martin, 1998).

For each variable, a multi-step process was used to determine the best and most parsimonious model for the data. This process began with fitting a fully unconditional random intercept model (without predictors at Level 1 or 2). In order to determine the most appropriate model of individual change, we examined change in model fit from the means only model to a linear model (with AGE in months as a predictor at Level 1), and subsequently to a quadratic model (including AGE^2 at Level 1). Chi-square tests of deviance were calculated to determine whether the linear or quadratic model lead to a significant reduction in deviance compared to the previous model (i.e., was a better fit for the data).

The appropriate model was selected based on the significance of the chi-square deviance test, the significance of the growth term, and the degree of variability on the random effect terms.

Higher order growth models were retained only if they significantly reduced the deviance (i.e. improved the fit) of the model and the growth term was significantly[1] greater than zero. A random effect was included on the growth term if the variance was significantly greater than zero.

Three types of models are reported below. When a variable had no significant growth, the unconditional random intercept model is reported. With no predictors, the unconditional means model reports the grand mean across ages for the variable in question. For coordination variables, the significance of the fixed effect of the intercept (β_{00}) indicates whether coordination is significantly greater than would be expected by chance. When a linear model was determined to be the best fit for the data, AGE (coded in months with 3 months as the intercept) was included in the model at Level 1. In the linear model, the fixed effect of the intercept (β_{00}) indicates the estimate at 3 months, while the fixed effect of AGE (β_{10}) indicates the direction and degree of linear change (i.e. estimated change in one month). Finally, when a quadratic model was the best fit for the data, AGE^2 was included at Level 1. With AGE^2 in the model, the fixed effect on the linear term (β_{10}) indicates the degree of instantaneous linear growth at the intercept (i.e. rate and direction of growth at the intercept time point), and the fixed effect on the quadratic term (β_{20}) indicates the degree of deceleration or acceleration in growth over time.

Once the appropriate model was determined, Risk Status was added to the model at Level 2 in order to examine differences between dyads with LR and HR infants. The Low Risk group served as the reference group, thus fixed effects coefficients describe intercept and growth for the LR group, and deviations in intercept and growth for dyads with HR infants. In the case that Risk Status was a significant predictor of growth (linear or quadratic), follow-up analyses were

[1] In 1 case (latency to respond coordination) a marginal quadratic term is described because the quadratic model was a significant improvement in fit and examination of the raw data indicated that a quadratic model was a better descriptor of the data.

conducted in order to determine at what age points LR and HR infants converged or diverged from each other by re-centering the intercept at 6, 9, and 12 months. In the case that Risk Status was not a significant predictor of the intercept or growth terms, unconditional models are reported below.

3.0 RESULTS

The present study was designed to describe the development of the dyadic coordination of vocalization and gaze behavior between mothers and infants across the first year of life in a group of infants at high and low risk for ASD, with the goal of understanding how coordination develops in a dyadic and multi-modal context, and how it relates to later development. In presenting the results, we first describe the development of *individual* parent and infant vocal and gaze behavior in dyads with LR vs. HR infants. Following this description, we turn to the results relevant to our primary aims. We begin by examining the coordination of mother and infant vocalizations and gaze respectively (note that the coordination of gaze to faces and gaze to toys are examined separately) and present analyses describing the development of coordination variables over time, with Risk Status differences described where relevant (Aims 1 and 2). Next, we explore relations between different measures of coordination (Aim 3) and between individual vocalization and gaze variables and coordination (Aim 4). This is followed by an examination of the development of multi-modal coordination (i.e. the coordination of gaze and vocalization behaviors; Aim 5). In a final set of analyses, we assess relations between coordination variables in different behavioral domains both concurrently and over time (Aim 6) and whether coordination in the first year relates to later language development (Aim 7).

3.1 INDIVIDUAL VOCAL AND GAZE BEHAVIORS

Table 3 presents the means and standard deviations for frequency of mother vocalizations and infant vocalizations, the proportion of infant vocalizations that were linguistic, non-linguistic, and affective, the proportion of linguistic vocalizations that contained consonants, and the proportion of mother and infant vocalizations that were directed to partner’s face, to toys, or to both face and toy (within one vocalization) at each age for dyads with LR and HR infants. Based on previous research, we did not expect to find differences between LR and HR infants in overall frequency of vocalizations or direction of vocalizations. However, we predicted that HR infants would produce a lower proportion of linguistic vocalizations and exhibit slower growth in consonant production than LR infants (Paul et al., 2011).

Table 3. Means and Standards Deviations for Vocalization Production

		Infant						Mother					
		LR			HR			LR			HR		
	Age	N	Mean	*SD*	N	Mean	*SD*	N	Mean	*SD*	N	Mean	*SD*
Frequency of Vocalizations	3	15	36.67	*28.46*	5	26.6	*15.24*	15	80.93	*17.54*	5	72.4	*9.71*
	6	14	34.93	*23.39*	12	36.5	*41.05*	14	67.93	*21.57*	12	71.08	*19.69*
	9	15	24.6	*25.75*	12	16.33	*14.37*	15	65.93	*16.44*	12	75.17	*17.3*
	12	15	28.2	*15.96*	8	26.63	*19.03*	15	73.4	*18.13*	8	70.88	*22.15*
Proportion Linguistic	3	15	0.82	*0.16*	5	0.8	*0.16*	-	-	-	-	-	-
	6	14	0.79	*0.16*	12	0.83	*0.14*	-	-	-	-	-	-
	9	15	0.78	*0.27*	12	0.84	*0.15*	-	-	-	-	-	-
	12	15	0.79	*0.25*	8	0.85	*0.12*	-	-	-	-	-	-
Proportion Non-Linguistic	3	15	0.11	*0.14*	5	0.19	*0.17*	-	-	-	-	-	-
	6	14	0.13	*0.14*	12	0.1	*0.13*	-	-	-	-	-	-
	9	15	0.21	*0.27*	12	0.15	*0.14*	-	-	-	-	-	-
	12	15	0.17	*0.25*	8	0.04	*0.07*	-	-	-	-	-	-
Proportion Affective	3	15	0.07	*0.11*	5	0.02	*0.03*	-	-	-	-	-	-
	6	14	0.08	*0.13*	12	0.06	*0.09*	-	-	-	-	-	-
	9	15	0.01	*0.03*	12	0.01	*0.02*	-	-	-	-	-	-
	12	15	0.03	*0.05*	8	0.11	*0.09*	-	-	-	-	-	-
Proportion Linguistic Vocalizations Containing Consonants	3	15	0.04	*0.05*	5	0.07	*0.1*	-	-	-	-	-	-
	6	14	0.06	*0.09*	12	0.03	*0.05*	-	-	-	-	-	-
	9	14	0.21	*0.23*	12	0.28	*0.25*	-	-	-	-	-	-
	12	14	0.24	*0.17*	8	0.52	*0.36*	-	-	-	-	-	-
Proportion Vocalizations Directed to Face	3	15	0.17	*0.18*	5	0.12	*0.12*	15	0.5	*0.22*	5	0.45	*0.2*
	6	14	0.06	*0.12*	12	0.04	*0.06*	14	0.32	*0.15*	11	0.18	*0.06*
	9	15	0.08	*0.15*	12	0.05	*0.1*	15	0.25	*0.12*	12	0.18	*0.08*
	12	15	0.06	*0.09*	8	0.05	*0.07*	14	0.24	*0.15*	8	0.22	*0.1*
Proportion Vocalizations Directed to Toys	3	15	0.41	*0.27*	5	0.55	*0.13*	15	0.18	*0.12*	5	0.23	*0.11*
	6	14	0.63	*0.17*	12	0.72	*0.22*	14	0.3	*0.15*	11	0.42	*0.14*
	9	15	0.66	*0.25*	12	0.68	*0.24*	15	0.38	*0.16*	12	0.41	*0.15*
	12	15	0.61	*0.2*	8	0.63	*0.24*	14	0.4	*0.17*	8	0.47	*0.15*
Proportion Vocalizations Directed to Face & Toy	3	15	0.02	*0.04*	5	0.03	*0.03*	15	0.29	*0.13*	5	0.29	*0.11*
	6	14	0.01	*0.02*	12	0.02	*0.03*	14	0.34	*0.14*	11	0.35	*0.13*
	9	15	0.01	*0.03*	12	0.01	*0.02*	15	0.34	*0.1*	12	0.33	*0.09*
	12	15	0.03	*0.03*	8	0.02	*0.03*	14	0.3	*0.08*	8	0.26	*0.06*

Table 4 presents the results of the final HLM models for these variables. As can be seen in Tables 3 and 4, there was no significant growth in the frequency of caregiver or infant vocalizations, and no significant differences between dyads with HR and LR infants in these variables. Infants produced primarily linguistic vocalizations (~80%) at every age, and there was no growth or significant difference between HR and LR infants in the proportion of vocalizations that were linguistic, non-linguistic, or affective. Risk Status was, however, a significant predictor of growth in the proportion of linguistic vocalizations containing consonants. However, contrary to our hypothesis, while both LR and HR infants displayed positive linear growth in consonant production from 3 to 12 months, HR infants had significantly faster growth than LR infants (see Table 4). Follow-up analyses revealed that HR infants produced a significantly higher proportion of consonants than LR infants at 9 (p = .043) and 12 months (p = .034).

Table 4. HLM Models for Vocalization Production

		Infant				Mother			
		β	SE	t (df)	p-value	β	SE	t (df)	p-value
Frequency Vocalizations	Intercept, β_{00}	29.08	2.94	9.9 (29)	<0.001	72.59	2.54	28.53 (29)	<0.001
Proportion Linguistic	Intercept, β_{00}	0.81	0.02	37.67 (29)	<0.001				
Proportion Non-Linguistic	Intercept, β_{00}	0.14	0.02	6.96 (29)	<0.001				
Proportion Affective	Intercept, β_{00}	0.05	0.01	5.21 (29)	<0.001				
Proportion Consonants	Intercept, β_{LR0}	0.03	0.04	0.77 (28)	0.449				
	HR, β_{LR0}	-0.09	0.07	-1.31 (28)	0.2				
	Linear Growth, β_{LR1}	0.02	0.01	2.72 (28)	0.011				
	HR, β_{HR1}	0.03	0.01	2.24 (28)	0.034				
Vocs Directed to Partner's Face	Intercept, β_{00}	0.12	0.02	4.99 (29)	<0.001	0.46	0.04	10.89 (29)	<0.001
	Linear Growth, β_{10}	-0.01	0.004	-2.12 (29)	0.043	-0.08	0.01	-5.31 (29)	<0.001
	Quadratic Growth, β_{20}	-	-	-	-	0.01	0.001	4.22 (29)	<0.001
Vocs Directed to Toys	Intercept, β_{00}	0.46	0.05	9.44 (29)	<0.001	0.19	0.03	6.51 (29)	<0.001
	Linear Growth, β_{10}	0.09	0.02	3.62 (64)	<0.001	0.06	0.01	4.38 (29)	<0.001
	Quadratic Growth, β_{20}	-0.01	0.002	-3.07 (64)	0.003	-0.003	0.001	-2.64 (33)	0.013
Vocs Directed to Face/Toy	Intercept, β_{00}	0.02	0.003	6.00 (29)	<0.001	0.32	0.01	23.17 (29)	<0.001

HLM models revealed no Risk Status differences in intercept or growth for any of the directed vocalization variables. Approximately 12% of infant vocalizations were directed at mother's face at 3 months, and the proportion of face directed vocalizations decreased linearly over time. Conversely, the proportion of infant vocalizations directed at toys was approximately 46% at 3 months and displayed quadratic growth, with significant positive instantaneous linear growth (i.e. increasing), and a small amount of deceleration (i.e. flattening) over time. Infants rarely directed their vocalizations to both toy and face (in one vocalization), and there was no significant change in this variable across the first year.

Mothers, on the other hand, directed approximately 46% of their vocalizations to infant's face and 19% to toys at 3 months. Across the first year, mothers reduced the proportion of vocalizations directed to face in a quadratic fashion, with negative instantaneous linear growth and a small amount of acceleration (i.e. flattening) over time, while increasing the proportion of vocalizations directed at toys, also in a quadratic fashion, with significant positive instantaneous linear growth and deceleration over time. Mothers directed about 33% of their vocalizations at both a toy and their infants face, and this variable did not display significant growth across infant development.

Table 5 presents means and standard deviations for infant and mother duration of time (in seconds) spent looking at faces, toys, and neither (undirected gaze), mean duration of gaze shifts, total frequency of gaze shifts, and rate of vocalizations (per 10 seconds) during gaze to faces and toys. Table 6 presents results of the final HLM models for these variables. Developmental trends for gaze durations looked similar to those seen for directed vocalizations. Across the first year, both mothers and infants decreased the amount of time they spent looking at faces in a quadratic fashion, with the biggest decreases between 3 and 6 months and a flattening in change over time, and they increased the amount of time spent looking at toys in a quadratic fashion, with the biggest increase occurring between 3 and 6 months and flattening in change over time. As can be seen in Tables 5 and 6, mothers spent much more time looking at infants' faces across all ages than infants spent looking at mothers' faces.

Both mothers and infants also increased the frequency and decreased the duration of their gaze shifts from 3 to 12 months. Infants displayed positive linear growth in frequency of gaze shifts from 3 to 12 months and negative linear growth in the mean length of gaze shifts, while mothers displayed quadratic growth in frequency of gaze shifts (with deceleration over time) and quadratic reduction in mean length of gaze shifts (with acceleration over time).

With regards to vocalization rates (rate of vocalizations per 10 seconds) during gaze to faces and toys, no effect of age and no Risk Status differences were apparent for any variables. Infants vocalized at a rate of about one vocalization per 10 seconds while looking to mother's faces on average, and had slightly lower vocalization rates ($\beta = 0.87$) while looking at toys. Mother's vocalizations rates, on the other hand, were slightly higher when looking to toys ($\beta = 2.47$) than when looking to infants' faces ($\beta = 2.23$).

Table 5. Means and Standard Deviations for Gaze Behavior

		Infant						Mother					
		LR			HR			LR			HR		
	Age	N	Mean	*SD*	N	Mean	*SD*	N	Mean	*SD*	N	Mean	*SD*
Duration Gaze Partner's Face	3	15	43.79	*54.67*	5	31.46	*19.15*	15	180.19	*55.28*	5	170.42	*46.7*
	6	14	15.4	*16.45*	12	8.34	*8.19*	14	126.91	*37.23*	11	97.48	*29.92*
	9	15	12.65	*13.76*	12	11.65	*13.49*	15	107.03	*42.63*	12	91.86	*32.76*
	12	15	20.79	*29.73*	8	12.91	*20.33*	14	91.89	*44.98*	8	80.26	*28.59*
Duration Gaze Toys	3	15	136.58	*78.15*	5	189.46	*37.57*	15	88.6	*44.43*	5	95.14	*30.24*
	6	14	194.44	*49.51*	12	217.74	*38.38*	14	131.49	*39.61*	11	160.59	*31.19*
	9	15	207.39	*28.96*	12	217.7	*26.44*	15	146.35	*37.32*	12	158.55	*39.24*
	12	15	200.63	*41.87*	8	211.43	*34.36*	14	156.05	*41.45*	8	156.67	*30.84*
Duration Gaze Undirected	3	15	119.63	*76.19*	5	79.08	*36.32*	15	31.22	*18.95*	5	34.43	*20.31*
	6	14	90.17	*39.66*	12	73.92	*37.52*	14	41.61	*13.53*	11	41.93	*14.98*
	9	15	79.96	*24*	12	70.65	*21.37*	15	46.62	*21.32*	12	49.59	*32.06*
	12	15	78.58	*28.9*	8	75.66	*28.6*	14	52.07	*22.17*	8	63.07	*8.76*
Mean Duration Gaze Shifts	3	15	5.25	*3.47*	5	4.52	*2.18*	15	2.9	*2.29*	5	1.89	*0.87*
	6	14	3.44	*1.40*	12	4.69	*4.03*	14	1.54	*0.56*	11	1.46	*0.36*
	9	15	2.98	*1.00*	12	3.47	*1.12*	15	1.38	*0.42*	12	1.27	*0.26*
	12	15	2.97	*1.04*	8	2.6	*0.61*	14	1.41	*0.26*	8	1.36	*0.27*
Total Frequency Gaze Shifts	3	15	49.27	*20.15*	5	60.6	*23.59*	15	128.67	*63.62*	5	167.8	*76.03*
	6	14	74.14	*21.09*	12	65.33	*22.56*	14	186.79	*59.17*	11	186	*42.98*
	9	15	91.27	*30.53*	12	81.25	*27.3*	15	200.53	*61.76*	12	203.75	*45.87*
	12	15	87.33	*20.68*	8	94.5	*17.07*	14	180.93	*33.88*	8	180	*33.49*
Vocalization Rate During Gaze to Toys	3	15	1.1	*0.87*	5	0.71	*0.35*	15	2.67	*0.52*	5	2.72	*0.59*
	6	14	1.08	*0.81*	12	1.12	*1.33*	14	2.28	*0.84*	11	2.53	*0.75*
	9	15	0.7	*0.76*	12	0.52	*0.51*	15	2.24	*0.56*	12	2.62	*0.57*
	12	15	0.75	*0.49*	8	0.75	*0.64*	14	2.35	*0.55*	8	2.37	*0.77*
Vocalization Rate During Gaze to Partner's Face	3	14	1.63	*1.46*	5	1.2	*0.85*	15	2.53	*0.73*	5	2.21	*0.4*
	6	14	1.09	*1.24*	11	0.85	*1.38*	14	2.22	*0.66*	11	1.88	*0.69*
	9	13	1.14	*1.53*	11	0.59	*1.24*	15	2.03	*0.65*	12	2.23	*0.68*
	12	14	0.63	*0.85*	7	1.36	*1.48*	14	2.44	*0.9*	8	2.15	*0.82*

Table 6. HLM Models for Gaze Behavior

		Infant				Mother			
		β	SE	t (df)	p-value	β	SE	t (df)	p-value
Gaze Partner	Intercept, β_{00}	34.42	9.23	3.73 (29)	<0.001	174.03	10.52	16.54 (29)	<0.001
	Linear Growth, β_{10}	-8.67	3.95	-2.2 (29)	0.036	-21.27	4.2	-5.07 (29)	<0.001
	Quadratic Growth, β_{20}	0.76	0.38	2.04 (29)	0.051	1.34	0.43	3.09 (29)	0.004
Gaze Toys	Intercept, β_{00}	153.98	14.53	10.6 (29)	<0.001	91.1	8.32	10.95 (29)	<0.001
	Linear Growth, β_{10}	20.05	5.17	3.87 (29)	<0.001	18.8	3.48	5.41 (29)	<0.001
	Quadratic Growth, β_{20}	-1.63	0.48	-3.42 (29)	0.002	-1.32	0.37	-3.52 (29)	0.001
Gaze Undirected	Intercept, β_{00}	108.18	11.71	9.24 (29)	<0.001	33.3	3.37	9.89 (29)	<0.001
	Linear Growth, β_{10}	-9.88	3.9	-2.53 (29)	0.017	2.47	0.62	3.99 (29)	<0.001
	Quadratic Growth, β_{20}	0.72	0.38	1.92 (35)	0.063	-	-	-	-
Avg. Duration Gaze Shift	Intercept, β_{00}	4.77	0.49	9.66 (29)	<0.001	2.33	0.37	6.37 (29)	<0.001
	Linear Growth, β_{10}	-0.23	0.08	-3.09 (29)	0.004	-0.3	0.11	-2.71 (29)	0.011
	Quadratic Growth, β_{20}	-	-	-	-	0.02	0.01	2.68 (29)	0.012
Total Gaze Shifts	Intercept, β_{00}	55.71	4.16	13.39 (29)	<0.001	138.98	13.79	10.08 (29)	<0.001
	Linear Growth, β_{10}	4.36	0.71	6.12 (29)	<0.001	21.22	5.75	3.69 (29)	<0.001
	Quadratic Growth, β_{20}	-	-	-	-	-1.84	0.56	-3.26 (29)	0.003
Voc. Rate During Gaze to Face	Intercept, β_{00}	1.02	0.14	7.33 (29)	<.001	2.23	0.09	23.90 (29)	<.001
Voc Rate During Gaze to Toys	Intercept, β_{00}	0.87	0.10	8.43 (29)	<.001	2.47	0.09	28.31(29)	<.001

3.2 DEVELOPMENT OF VOCALIZATION AND GAZE COORDINATION

3.2.1 Vocal Coordination.

Table 7 presents raw means and standard deviations for measures of vocal coordination across all four ages for dyads with HR and LR infants, and Table 8 displays the results of the final HLM models for these variables. We hypothesized that vocal coordination would be apparent as early as 3 months, that coordination would improve over the course of the first year, and that HR infants would display slower growth in coordination as compared to LR infants.

Table 7. Means and Standard Deviations for Vocal Coordination Measures

			LR			HR		
		Age	N	Mean	SD	N	Mean	SD
Simultaneous Speech	Recurrence at lag 0	3	15	-0.0042	*0.0069*	5.00	0.0011	*0.0061*
		6	14	-0.0035	*0.0065*	12.00	-0.0030	*0.0060*
		9	15	-0.0026	*0.0071*	12.00	-0.0011	*0.0055*
		12	15	-0.0046	*0.0100*	8.00	-0.0053	*0.0094*
	Adjusted Freq Mother Simultaneous Speech	3	15	-0.13	*1.78*	5.00	-0.22	*1.85*
		6	14	-1.96	*4.52*	12.00	-0.86	*3.05*
		9	15	-0.89	*2.84*	12.00	-0.57	*1.19*
		12	15	0.28	*2.53*	8.00	-1.95	*2.37*
	Adjusted Freq Infant Simultaneous Speech	3	15	-3.18	*3.55*	5.00	-0.06	*1.23*
		6	14	-1.25	*3.13*	12.00	-1.40	*2.94*
		9	15	-1.06	*1.98*	12.00	-1.18	*1.39*
		12	15	-1.90	*3.36*	8.00	-1.51	*2.33*
Infant Leading, Mother Following	Max Recurrence	3	15	0.0107	*0.0071*	5.00	0.0130	*0.0034*
		6	14	0.0119	*0.0097*	12.00	0.0085	*0.0040*
		9	15	0.0102	*0.0066*	12.00	0.0101	*0.0072*
		12	15	0.0150	*0.0118*	8.00	0.0134	*0.0096*
	Adjusted Frequency Contingent Responses	3	15	1.04	*2.42*	5.00	2.91	*2.86*
		6	14	2.23	*2.56*	12.00	1.27	*1.65*
		9	15	1.93	*2.34*	12.00	1.62	*2.16*
		12	15	1.40	*2.94*	8.00	2.72	*2.88*
	Mean Latency to Respond	3	15	1.42	*1.38*	5.00	1.56	*0.89*
		6	14	1.41	*1.11*	12.00	2.03	*1.96*
		9	14	1.99	*1.61*	12.00	2.38	*3.03*
		12	15	1.53	*0.98*	8.00	1.74	*1.32*
Mother Leading, Infant Following	Max Recurrence	3	15	0.0178	*0.0113*	5.00	0.0146	*0.0054*
		6	14	0.0158	*0.0157*	12.00	0.0133	*0.0126*
		9	15	0.0110	*0.0147*	12.00	0.0095	*0.0101*
		12	15	0.0136	*0.0108*	8.00	0.0093	*0.0068*
	Adjusted Frequency Contingent Responses	3	15	2.06	*2.55*	5.00	0.61	*1.63*
		6	14	0.42	*1.94*	12.00	0.81	*1.94*
		9	15	1.02	*2.08*	12.00	1.18	*2.09*
		12	15	1.62	*3.10*	8.00	1.63	*2.01*
	Mean Latency to Respond	3	15	1.49	*1.44*	5.00	2.42	*0.95*
		6	14	3.01	*3.45*	12.00	2.59	*2.61*
		9	14	3.21	*1.93*	12.00	2.40	*1.90*
		12	15	2.29	*1.51*	8.00	2.20	*0.90*
	Latency to Respond Coordination	3	15	0.39	*0.31*	5.00	1.36	*1.06*
		6	14	1.99	*3.54*	12.00	1.65	*2.76*
		9	14	1.44	*1.53*	12.00	1.23	*0.94*
		12	15	1.17	*1.19*	8.00	0.80	*0.66*

3.2.1.1 Simultaneous Speech.

Three measures of simultaneous speech were analyzed: total simultaneous recurrence of mother and infant vocalizations (recurrence at lag zero), frequency infant simultaneous speech, and frequency mother simultaneous speech. HLM models for these three variables revealed no significant growth terms, and no significant effects of infant risk status. Thus, the unconditional random intercept models are reported. For all three measures of simultaneous speech, rates were significantly less than would be expected by chance, indicating that mothers and infants inhibited speech when their partners vocalized. As can be seen in Table 8, mothers and infants spent significantly less time in simultaneous speech than would be expected by chance. Mothers began vocalizing during their infants' vocalizations approximately 0.76 fewer times than would be expected by chance, while infants began speaking during their mothers' vocalizations approximately 1.6 fewer times than would be expected by chance. Thus, while both mothers and infants inhibited their speech when their partner was speaking, infants were somewhat more likely to do so in relation to chance.

Table 8. HLM Models for Vocal Coordination Measures

		β	SE	t (df)	p-value
Simultaneous Recurrence	Intercept, β_{00}	-0.003	0.001	-4.27 (29)	<0.001
Caregiver Adjusted Frequency Simultaneous Speech	Intercept, β_{00}	-0.76	0.3	-2.5 (29)	0.018
Infant Adjusted Frequency Simultaneous Speech	Intercept, β_{00}	-1.58	0.31	-5.12 (29)	<0.001
Infant Leading, Mother Following					
Max Recurrence	Intercept, β_{00}	0.01	0	13.73 (29)	<0.001
Frequency Contingent Response	Intercept, β_{00}	1.75	0.25	6.98 (29)	<0.001
Latency to Respond	Intercept, β_{00}	1.75	0.19	9.26 (29)	<0.001
Mother Leading, Infant Following					
Max Recurrence	Intercept, β_{00}	0.01	0	10.03 (29)	<0.001
Frequency Contingent Response	Intercept, β_{00}	1.23	0.26	4.81 (29)	<0.001
Latency to Respond	Intercept, β_{00}	2.44	0.24	10.3 (29)	<0.001
Pause Coordination	Intercept, β_{00}	0.7	0.3	2.32 (29)	0.028
	Linear Growth, β_{10}	0.38	0.2	1.88 (29)	0.07
	Quadratic Growth, β_{20}	-0.04	0.02	-1.71 (29)	0.098

3.2.1.2 Infant leading/mother following.

With regard to mother vocalizations following infant vocalizations, we analyzed the max recurrence rate (with vocalization durations fixed at 1 second), frequency of contingent vocal responses (occurring within 2 seconds of the end of an infant's vocalization), and average duration latency to respond (see Table 8). For all three measures of infant leading/mother following, HLM models revealed no significant effects of infant age and no risk status differences. Therefore, unconditional random intercept models are reported. Max recurrence for infants leading/mothers following was significantly greater than would be expected by chance and mothers responded to their infants' vocalizations contingently more often than would be expected by chance. On average, mothers' latency to respond was about 1.75 seconds.

3.2.1.3 Mother leading/infant following.

Analysis of measures of infant vocal behavior following mother vocal behavior also revealed no change across age and no risk status differences. Max recurrence for infants following mothers was significantly different from zero, and quite similar to the recurrence rate for mothers following infants. Infants also responded to their mothers contingently more than would be expected by chance and at a similar rate to mothers. Average infant duration latency to respond was a bit longer than mothers, averaging around 2.44 seconds.

3.2.1.4 Latency to Respond Coordination.

Next, we examined the degree to which infants' and mothers' latencies to respond were similar (latency to respond difference score; see Table 2 for definition). Contrary to our expectations, difference scores were lowest (i.e. mother and infant latencies to respond were most similar) when infants were 3 months old, and showed an initial increase from 3 to 6 months followed by a steady decrease. The final HLM model revealed that at 3 months the latency to respond difference score was around 0.7, and it displayed marginally significant positive instantaneous linear growth, along with marginally significant deceleration across age. Risk status was not a significant predictor in this model.

3.2.1.5 Relations among Vocal Coordination Variables.

Table 9 displays the correlations among measures of vocal coordination. We hypothesized that the various measures of vocal coordination (e.g. simultaneous speech, recurrence, contingency, and latency to respond coordination) described here would be related to one another, providing evidence that these aspects of vocal coordination work together to create a predictable, rhythmic interaction. We also expected that measures of infant leading/mother following would be related to measures of mother leading/infant following, such that mothers who had more and faster vocal responses would have infants with more and faster vocal responses.

As can be seen Table 9, these hypotheses were generally supported. Infant max recurrence, frequency infant contingent responses, infant latency to respond, mother max recurrence, frequency mother contingent responses, and mother latency to respond were all either significantly or marginally correlated, with r's between .17 and .52. Mothers and infants with higher recurrence had more contingent responses and shorter latencies to respond, and also had infants with these same qualities. Lower measures of simultaneous speech, or the degree to which infants and mother inhibited their speech during a partner's vocalizations, were also variably associated with these measures of coordination. Greater latency to respond coordination (i.e. lower difference scores) was associated with higher infant max recurrence, shorter infant pause durations, more maternal contingent responses, and less simultaneous speech.

Table 9. Relations Between Vocal Coordination Variables

Variable	1	2	3	4	5	6	7	8	9	10
1. Simultaneous Recurrence	-	.48**	.61**	-0.2	-.26*	0.14	-0.10	-.26*	.24*	.22*
2. Caregiver Adjusted Frequency Simultaneous Speech		-	0.06	-0.02	-.47**	0.13	-.36**	0.02	0.18	0.18
3. Infant Adjusted Freq. Simultaneous Speech			-	-.22*	-0.16	0.14	-0.04	-.48**	.30**	.25*
4. Max Recurrence Infant Leading, Mother Following				-	.37**	-.29**	.43**	.52**	-.30**	-0.19
5. Freq Mother Contingent Responses					-	-.30**	.22*	.21*	-0.18	-0.11
6. Mother Latency to Respond						-	-.29**	-0.17	.36**	0.02
7. Max Recurrence Mother Leading, Infant Following							-	.34**	-.43**	-.29**
8. Freq Infant Contingent Response								-	-.46**	-.35**
9. Infant Latency to Respond									-	.85**
10. Latency to Respond Coordination										-

3.2.1.6 Relations between Vocal Coordination Composite and Individual Behaviors.

Cronbach's alphas for standardized vocal coordination variables exceeded .7 at every age, and thus a vocal coordination composite variable was created by averaging together standardized scores for all variables (scores were reversed for measures of simultaneous speech, latency to respond, and latency to respond coordination). With regard to relations between vocal coordination and individual vocal behavior, we hypothesized that dyads with infants who vocalized more, had a higher proportion of linguistic vocalizations, and produced a higher proportion of consonants would be more coordinated.

Table 10 displays the correlations between the vocal coordination composite and measures of individual mother and infant vocal behavior at each age. As hypothesized, at every age, higher vocal coordination was related to a higher frequency of infant vocalizations, and it was also related to a higher frequency of mother vocalizations (despite the fact that all coordination measures control for chance recurrence). Additionally, consistent with hypotheses, at 6 and 9 months infants with a higher proportion of consonants also had higher vocal coordination composite scores.

With regard to vocalization direction, we hypothesized that proportion of mother and infant vocalizations directed toward faces would relate to higher vocal coordination. As can be seen in Table 10, vocal coordination did not relate to infant vocal direction at any age. However, at 9 months, vocal coordination was positively related to the proportion of mother vocalizations that were directed at infants' face and object (within one vocalization) and negatively correlated with the proportion of mother vocalizations directed at objects. And at 12 months, vocal coordination was positively correlated with proportion of mother vocalizations directed at infant's face.

Table 10. Relations between Vocal Coordination Variables and Individual Vocal Behaviors

	Vocalization Coordination Composite			
	3 months	6 months	9 months	12 months
Frequency Caregiver Vocalizations	.562**	.390*	.465*	.500*
Frequency Infant Vocalizations	.605**	.664**	.783**	.627**
Proportion Linguistic	-0.258	0.366	0.021	0.391
Proportion Non-Linguistic	0.172	-0.204	-0.03	-0.401
Proportion Affective	0.147	-0.244	0.069	-0.001
Proportion Consonants	0.006	.642**	.650**	-0.171
Mother Vocs Directed to Partner's Face	0.115	0.073	0.158	.430*
Mother Vocs Directed to Toys	-0.113	0.023	-.457*	-0.32
Mother Vocs Directed to Face/Toy	-0.069	-0.121	.489**	0.125
Infant Vocs Directed to Partner's Face	0.339	0.031	0.212	0.382
Infant Vocs Directed to Toys	-0.194	-0.19	0.023	-0.202
Infant Vocs Directed to Face/Toy	0.188	0.228	0.053	0.37

3.2.2 Gaze Coordination.

Figures 4 and 5 display the mean recurrence plots for coordination of gaze to faces and coordination of gaze to objects respectively at 3, 6, 9, and 12 months.

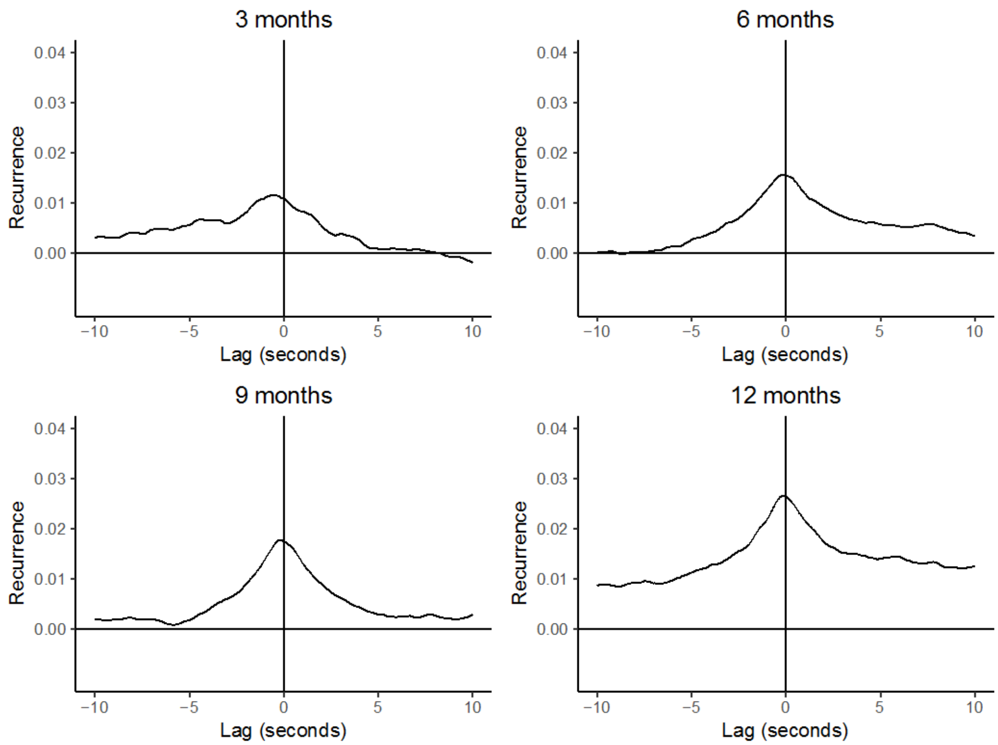


Figure 4. Adjusted Mean Recurrence Plots for Simultaneous Attention to Faces at 3, 6, 9, and 12 months

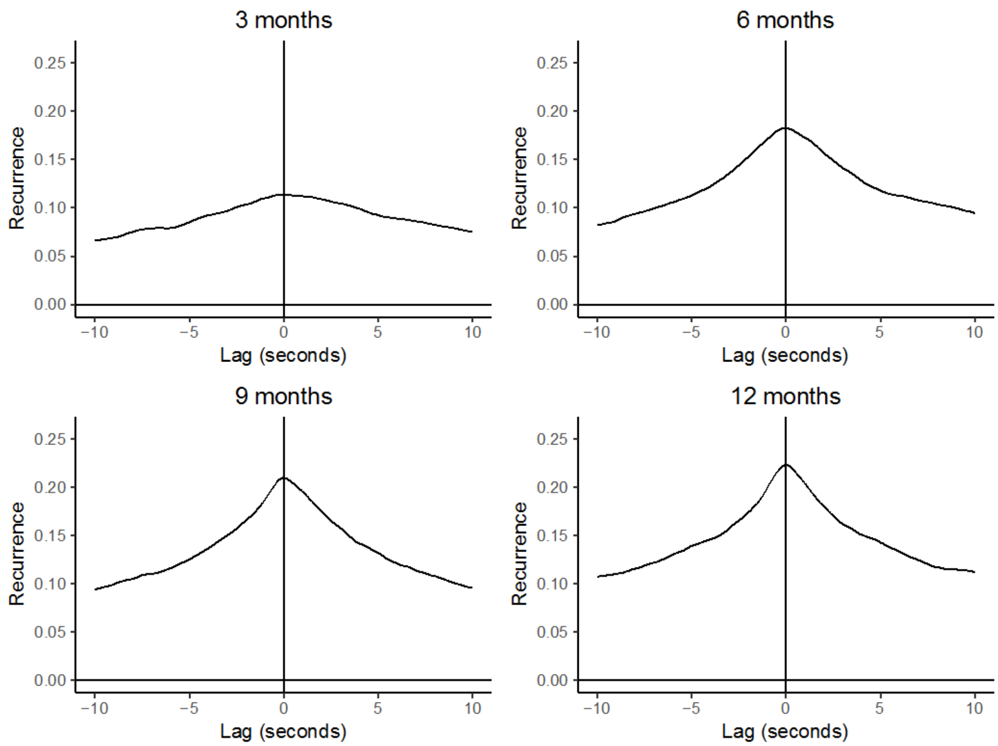


Figure 5. Adjusted Mean Recurrence Plots for Simultaneous Attention to Objects at 3, 6, 9, and 12 months

Points to the left of lag zero indicate infant leading/mother following, and points to the right of lag zero indicate mother leading/infant following.

3.2.2.1 Simultaneous Attention to Faces.

Table 11 displays means and standard deviations for measures of simultaneous attention to faces (mutual gaze) coordination across the first year in dyads with HR and LR infants, and Table 12 displays the final HLM models for these variables. It was hypothesized that coordination of gaze to faces would be significantly different from chance starting at 3 months and would improve over time.

Table 11. Means and Standard Deviations for Mutual Gaze Coordination

			LR			HR		
		Age	N	Mean	*SD*	N	Mean	*SD*
	Raw Recurrence Mutual Gaze	3	15	0.119	*0.154*	5	0.073	*0.046*
		6	14	0.046	*0.048*	11	0.021	*0.021*
		9	15	0.04	*0.045*	12	0.032	*0.042*
		12	14	0.063	*0.091*	8	0.039	*0.062*
	Adjusted Recurrence at Lag 0	3	15	0.013	*0.020*	5	0.006	*0.01*
		6	14	0.019	*0.015*	11	0.011	*0.009*
		9	15	0.019	*0.019*	12	0.016	*0.018*
		12	14	0.029	*0.033*	8	0.022	*0.029*
Infant Leading, Mother Following	Mean Recurrence within 5 seconds	3	15	0.009	*0.017*	5	0.005	*0.007*
		6	14	0.009	*0.009*	11	0.005	*0.006*
		9	15	0.006	*0.008*	12	0.01	*0.015*
		12	14	0.019	*0.026*	8	0.012	*0.019*
	Frequency Follows	3	15	0.991	*1.936*	5	0.848	*1.282*
		6	14	-0.858	*0.941*	11	0.284	*1.109*
		9	15	-0.354	*1.378*	12	0.083	*1.747*
		12	14	0.002	*1.062*	8	-0.338	*1.909*
	Mean Latency to Follow	3	10	0.795	*0.78*	5	0.55	*0.474*
		6	6	0.277	*0.247*	6	0.763	*0.634*
		9	9	0.352	*0.274*	9	0.571	*0.214*
		12	9	0.356	*0.134*	3	0.244	*0.213*
Mother Leading, Infant Following	Mean Recurrence within 5 seconds	3	15	0.006	*0.02*	5	0	*0.005*
		6	14	0.013	*0.011*	11	0.003	*0.007*
		9	15	0.007	*0.008*	12	0.01	*0.015*
		12	14	0.021	*0.028*	8	0.011	*0.021*
	Frequency Follows	3	15	1.162	*1.822*	5	0.592	*1.491*
		6	14	1.639	*1.466*	11	1.577	*1.439*
		9	15	3.157	*3.057*	12	1.26	*1.52*
		12	14	2.271	*2.445*	8	2.31	*1.698*
	Mean Latency to Follow	3	13	2.845	*1.202*	5	3.225	*3.121*
		6	13	2.482	*0.973*	10	1.487	*1.312*
		9	13	1.906	*0.758*	10	2.022	*1.05*
		12	12	1.691	*1.641*	7	1.343	*0.592*

Table 12. HLM Models for Mutual Gaze Coordination

		β	SE	t (df)	p-value
Simultaneous Recurrence	Intercept, β_{00}	0.011	0.004	2.78 (29)	0.01
	Linear Growth, β_{10}	0.002	0.001	2.47 (63)	0.016
Infant Leading, Mother Following					
Max Recurrence	Intercept, β_{00}	0.01	0.002	5.55 (29)	<0.001
Frequency Follows to JA	Intercept, β_{00}	0.789	0.363	2.17 (29)	0.038
	Linear Growth, β_{10}	-0.411	0.176	-2.33 (29)	0.027
	Quadratic Growth, β_{20}	0.035	0.017	2.08 (29)	0.047
Mother Leading, Infant Following					
Max Recurrence	Intercept, β_{00}	0.004	0.003	1.42 (29)	0.166
	Linear Growth, β_{10}	0.001	0.001	2.3 (63)	0.025
Frequency Follows to JA	Intercept, β_{00}	1.163	0.324	3.59 (29)	0.001
	Linear Growth, β_{10}	0.157	0.068	2.3 (29)	0.029
Latency Follows to JA	Intercept, β_{00}	2.732	0.277	9.86 (29)	<0.001
	Linear Growth, β_{10}	-0.138	0.049	-2.82 (29)	0.009

Recurrence at lag 0.

While the raw amount of time infants and mothers spent in mutual gaze decreased over time (see Table 11), the recurrence of infants' and mother's gaze to partner's face increased over time when adjusted for chance (see Table 11 and Figure 4). Thus, while infants and mothers reduced the raw amount of time they spent looking at each other's faces, they increased in the coordination of the timing of these looks. Consistent with our hypotheses, recurrence at lag zero was significantly greater than chance at 3 months and showed significant positive linear growth over time (see Table 12). There were no Risk Status differences.

Infant leading/mother following.

Mean recurrence of infant leading/mother following within 5 seconds of mutual gaze was significantly greater than would be expected by chance, and did not show significant change over time. Despite significant recurrence, the average frequency of mother following infant to mutual gaze (i.e. infant looks to mother's face and then mother looks to infant's face) was close to zero (see Table 12). This is likely because the frequency measure for mother following infant to mutual gaze requires that mothers were not looking to their infant's face at the moment the infant shifted his/her gaze to mother's face, and thus more cleanly captures how moments of mutual gaze begin. Given how much mothers looked at infants faces and how little infants looked to mothers faces overall (see Table 5), it was rare for infants to look to their mothers' faces at a time when mothers were not already looking at their infants' faces. In fact, 24% of dyads at 3 months, 52% of dyads at 6 months, 33.3% of dyads at 9 months, and 45.5% of dyads at 12 months had zero instances of mother following infant to mutual gaze.

HLM analysis of this variable indicated a quadratic model of growth. At 3 months, mother following infant to mutual gaze was infrequent, but significantly more common than would be expected by chance, with significant negative instantaneous linear growth and an accelerating pattern over time. This indicates a U-shaped pattern whereby mothers were most likely to follow their infants' gaze to face at 3 months, reduced sharply between 3 and 6 months, and then increased somewhat between 9 and 12 months. The frequency with which mothers followed infants' gaze to face was not significantly different from chance at any age other than 3 months. Given how infrequently mothers followed infants to mutual gaze, we did not analyze latencies for this variable.

Mother leading/infant following.

Mean recurrence for infant following mother within a 5 second lag was not significantly different from zero at 3 months, but showed significant positive linear growth over time and was significantly greater than chance by the 6 month age point ($p < .001$). Frequency of infant following mothers' gaze to face was much more common than mothers following infants. Infants followed their mothers gaze to face more than would be expected by chance at 3 months, and showed positive linear growth in following over time. There were no Risk Status differences.

Infants also became faster at following their mother's gaze to face over time. At 3 months, infants' latency to follow was approximately 2.73 seconds on average, and they showed significant negative linear growth over time such that by 12 months infants were following their mothers' gaze to face in 1.48 seconds on average.

Relations among Mutual Gaze Coordination Variables.

Table 13 displays correlation coefficients for the relations among mutual gaze coordination variables (note that latency for mother to follow is not included due to low frequency). We hypothesized that measures of recurrence would relate to event based measures of coordination, and that measures of infant leading/mother following would related to measures of mother leading/infant following. As can be seen in the table, the frequency of infant following mother's gaze to face was correlated with all three measures of recurrence. Contrary to our expectations, frequency of mother following infant's gaze to face was significantly negatively correlated with other coordination variables, indicating that dyads who had more instances of mother following infant gaze to mutual gaze (i.e. infant looked to mother first, and then mother looked to infant) had fewer instances of infant following mother to mutual gaze, and less mutual gaze recurrence overall. Latency for infant to follow mothers gaze to face was not related to any other variable.

Table 13. Relations between Mutual Gaze Coordination Variables

Variable	1	2	3	4	5	6
1. Simultaneous Recurrence	-	.92**	-.32**	.92**	.41**	-0.10
2. Mean Recurrence Infant Leading, Mother Following		-	-.27**	.95**	.23*	-0.03
3. Freq Mother Follows Infant			-	-.38**	-.35**	-0.05
4. Mean Recurrence Mother Leading, Infant Following				-	.28**	-0.03
5. Freq Infant Follows Mother					-	-0.15
6. Infant Latency to Follow						-

Relation between Mutual Gaze Coordination Composite and Individual Behaviors.

With all variables included except latency for infant to follow mother, Cronbach's alpha exceeded .7 at each age, thus a mutual gaze coordination composite variable was created by standardizing and averaging together coordination variables (with frequency mother follow infant reverse scored). We hypothesized that mutual gaze coordination would be related to the frequency and duration of mother and infant gaze shifts as well as the rate of vocalizations during gaze to face. Table 14 displays correlation coefficients for relations between the mutual gaze coordination composite at each age and individual measures of gaze and directed vocalization behavior. At 6, 9, and 12 months, infants with more (and generally shorter, although these correlations were not all significant) gaze shifts also had higher mutual gaze coordination. The relation between infant vocalization rate during gaze to face was significant only at 9 months, and at this age mutual gaze coordination was related to vocalization rate during gaze to objects as well (all the relationship with rate of vocalizations during gaze to face was stronger). Contrary to our expectations, mother's vocalization rate during gaze to face was not related to mutual gaze coordination at any age.

Table 14. Relations between Mutual Gaze Coordination Composite and Individual Gaze Behaviors

	Face Gaze Coordination Composite			
	3 months	6 months	9 months	12 months
Mother Total Frequency Gaze Shifts	-0.237	0.12	0.055	0.153
Mother Mean Duration Gaze Shifts	0.137	-0.15	-0.045	-0.056
Mother Voc Rate During Gaze to Toys	0.176	0.082	0.08	0.317
Mother Voc Rate During Gaze to Face	0.358	0.273	0.133	.701**
Infant Total Frequency Gaze Shifts	-0.287	.544**	.526**	.423*
Infant Mean Duration Gaze Shifts	0.365	-0.34	-.497**	-0.246
Infant Voc Rate During Gaze to Toys	0.343	-0.294	.398*	0.194
Infant Voc Rate During Gaze to Face	0.21	0.022	.602**	0.209

3.2.2.2 Simultaneous Attention to Objects.

Table 15 displays means and standard deviations for measures of gaze coordination with objects across the first year in dyads with HR and LR infants, and Table 16 presents the results of final HLM models for these variables. We hypothesized that coordination of gaze to objects would not be significantly greater than chance at 3 months, and would be primarily led by mothers at this age. Across the first year, we predicted an increase in coordination as well as an increase in the equality of mother leading and infant leading interactions.

Table 15. Means and Standard Deviations for Object Gaze Coordination Variables

		LR			HR		
		N	Mean	*SD*	N	Mean	*SD*
Infant Leading, Mother Following	Recurrence at Lag 0	15	0.11	*0.08*	5	0.13	*0.05*
		14	0.18	*0.07*	11	0.19	*0.06*
		15	0.21	*0.08*	12	0.21	*0.1*
		14	0.24	*0.08*	8	0.20	*0.05*
	Mean Recurrence within 5 seconds	15	0.09	*0.07*	5	0.12	*0.05*
		14	0.14	*0.06*	11	0.15	*0.06*
		15	0.15	*0.07*	12	0.16	*0.09*
		14	0.18	*0.07*	8	0.15	*0.05*
	Frequency Follows	15	3.17	*2.13*	5	3.70	*2.12*
		14	9.99	*5.91*	11	9.44	*5.15*
		15	11.23	*6.96*	12	10.87	*6.14*
		14	12.43	*7.56*	8	11.88	*4.96*
	Mean Latency to Follow	14	1.51	*0.86*	5	2.31	*1.52*
		14	1.33	*0.53*	11	1.42	*0.76*
		15	1.12	*0.56*	12	1.1	*0.34*
		14	1.05	*0.44*	8	1.1	*0.26*
Mother Leading, Infant Following	Mean Recurrence within 5 seconds	15	0.1	*0.07*	5	0.13	*0.05*
		14	0.14	*0.07*	11	0.15	*0.06*
		15	0.16	*0.07*	12	0.16	*0.09*
		14	0.18	*0.07*	8	0.15	*0.04*
	Frequency Follows	15	3.29	*3.04*	5	5.64	*4.74*
		14	5.77	*2.89*	11	6.44	*5.29*
		15	9.67	*3.79*	12	9.08	*4.91*
		14	9.14	*4.47*	8	10.43	*5.91*
	Mean Latency to Follow	14	0.82	*0.41*	5	1.63	*0.81*
		14	0.97	*0.49*	11	1.26	*0.5*
		15	0.85	*0.31*	12	0.92	*0.27*
		14	0.89	*0.28*	8	0.89	*0.25*

Table 16. HLM Models of Object Gaze Coordination Variables

		β	SE	t (df)	p-value
Simultaneous Recurrence	Intercept, β_{00}	0.13	0.01	8.92 (29)	<0.001
	Linear Growth, β_{10}	0.01	0.003	4.54 (29)	<0.001
Infant Leading, Mother Following					
Max Recurrence	Intercept, β_{00}	0.11	0.01	8.06 (29)	<0.001
	Linear Growth, β_{10}	0.01	0.002	3.33 (29)	0.002
Frequency Follows to JA	Intercept, β_{00}	3.61	0.82	4.43 (29)	<0.001
	Linear Growth, β_{10}	2.18	0.5	4.36 (29)	<0.001
	Quadratic Growth, β_{20}	-0.14	0.05	-2.67 (29)	0.012
Latency Follows to JA	Intercept, β_{00}	1.63	0.18	9.19 (29)	<0.001
	Linear Growth, β_{10}	-0.07	0.02	-2.9 (29)	0.007
Mother Leading, Infant Following					
Max Recurrence	Intercept, β_{00}	0.11	0.01	7.8 (29)	<0.001
	Linear Growth, β_{10}	0.01	0.002	3.28 (29)	0.003
Frequency Follows to JA	Intercept, β_{00}	4.16	0.74	5.66 (29)	<0.001
	Linear Growth, β_{10}	0.71	0.15	4.84 (29)	<0.001
Latency Follows to JA	Intercept, β_{LR0}	0.85	0.11	7.87 (28)	<0.001
	HR, β_{LR0}	0.65	0.19	3.5 (28)	0.002
	Linear Growth, β_{LR1}	0.005	0.02	0.27 (28)	0.786
	HR, β_{HR1}	-0.09	0.03	-2.94 (28)	0.007

Recurrence at Lag 0.

Mothers and infants engaged in simultaneous attention to objects significantly more than would be expected by chance starting at 3 months of age, and recurrence improved over time. As can be seen in Table 15 and Figure 5, dyads spent approximately 12% of the time in simultaneous attention to objects (controlled for chance recurrence) at 3 months, and increased steadily over time such that by 16 months they were spending about double that time simultaneously looking at toys. The HLM model revealed that the proportion of time mothers and infants spent attending to the same toy at the same moment was significantly greater than chance at 3 months and showed significant linear growth over time (see Table 16). There were no risk status differences.

Infant leading/mother following.

Risk Status was not a significant predictor of any measures of infant leading/mother following in simultaneous attention to objects, and thus is not included in any of the models reported here. Mean recurrence of infant leading/mother following within 5 seconds of lag zero was significantly greater than chance at 3 months and showed significant linear growth over time. The frequency with which mothers followed their infants' gaze to simultaneous attention showed a pattern of positive, but decelerating quadratic growth over time, such that mothers' following increased more between 3 and 6 months than between 9 and 12 months. The HLM model revealed that mothers were already following their infants' gaze more than would be expected by chance at 3 months, and there was significant positive instantaneous linear growth and a small but significant amount of deceleration over time.

Mothers' latency to follow their infants' gaze also became shorter over time. Mothers followed their infants' gaze in approximately 1.6 seconds on average at 3 months, and gaze follow times decreased linearly by about -.07 seconds per month, such that by 12 months mothers were following their infants' gaze in a little less than a second on average, $\beta_{00} = 0.98$, $t(29) = 11.90$, $p < .001$.

Mother leading/infant following.

Recurrence of mother leading/infant following within a 5 second lag showed a very similar pattern. Mean recurrence was significantly greater than chance at 3 months and showed significant linear growth over time. There were no risk status differences in intercept or growth. Infants also followed their mothers' gaze to simultaneous gaze more than would be expected by chance starting at 3 months and showed significant positive linear growth in this variable. Again, Risk Status was not a significant predictor in this model.

As can be seen in Table 16, Risk Status was a significant predictor of both the 3 month intercept and linear growth in the model of latency to follow gaze. LR infants followed their mothers' gaze in about 0.85 seconds on average at 3 months, and showed no significant change in latency to follow over time. HR infants were about 0.65 seconds slower to follow their mothers' gaze at 3 months, but showed significantly more negative linear growth over time such that they no longer differed from LR infants in intercept by 9 months.

Relations among gaze coordination variables.

Next, we turn to the relations between measures of gaze coordination to objects. It was hypothesized that recurrence rates and event based measures of coordination would be related, and that measures of mother leading/infant following would be positively related to measures of infant leading/mother following. Table 17 displays the bivariate correlations between measures of gaze coordination to objects. As can be seen in the table, recurrence of mother and infant gaze at lag 0 (or the adjusted total time spent in simultaneous attention) was positively associated with higher frequencies of infant following mother and higher frequencies of mother following infant to simultaneous attention to an object, as well as shorter latencies of mothers following infant's gaze. Furthermore, as hypothesized, mean recurrence, frequency, and lag times for infants following mothers gaze were respectively associated with mean recurrence, frequency, and lag times for mother following infant gaze, such that mothers with higher recurrence, more follows, and faster latencies to follow had infants with higher recurrence, more follows, and faster latencies to follow.

Table 17. Relations between Object Coordination Variables

Variable	1	2	3	4	5	6	7
1. Simultaneous Recurrence	-	.96**	.23*	-.29**	.95**	.42**	0.001
2. Mean Recurrence Infant Leading, Mother Following		-	0.04	-.21*	.98**	.28**	0.08
3. Freq Mother Follows Infant			-	-.30**	-0.02	.26*	-0.12
4. Mother Latency to Follow				-	-0.20	-.25*	.26*
5. Mean Recurrence Mother Leading, Infant Following					-	.31**	0.10
6. Freq Infant Follows Mother						-	-0.15
7. Infant Latency to Follow							-

Relations between Gaze Coordination Composite and Individual Behaviors.

Examination of Cronbach's alpha for measures of simultaneous attention to objects at each age revealed that frequency of mother follows infant and latency of infant follows mother did not fit well with other coordination variables at any age. With these two variables removed, Cronbach's alpha exceeded .7 at all ages except 6 months (Cronbach's alpha = .68). At 6 months, frequency of infant follows was also removed, bringing the Cronbach's alpha to .82. Object gaze coordination composite scores for each month were created by standardizing and averaging relevant coordination variables.

It was predicted that object gaze coordination would be positively related to the rate of vocalizations during gaze to objects and to the frequency and duration of mother and infant gaze shifts. Table 18 displays correlations between the object gaze coordination composite and measures of individual mother and infant gaze behavior (frequency and duration of gaze shifts) and rate of vocalizations during gaze. At 3 months mothers with more and shorter gaze shifts and a higher rate of vocalizations during gaze to toys had higher gaze coordination. None of these relations were apparent at later ages, and infant rate of vocalization during gaze to objects did not relate to gaze coordination at any age. At 6 and 9 months infants with *fewer* and *longer* gaze shifts had better object gaze coordination.

Table 18. Relations between Object Gaze Coordination Composite and Individual Gaze Behaviors

	Object Gaze Coordination Composite			
	3 months	6 months	9 months	12 months
Mother Total Frequency Gaze Shifts	.777**	-0.133	0.051	-0.054
Mother Mean Duration Gaze Shifts	-.542*	0.225	0.026	0.142
Mother Voc Rate During Gaze to Toys	.522*	0.291	0.238	0.125
Mother Voc Rate During Gaze to Face	-0.093	0.291	0.274	-0.129
Infant Total Frequency Gaze Shifts	0.015	-.457*	-.388*	-0.248
Infant Mean Duration Gaze Shifts	0.184	.399*	.510**	0.318
Infant Voc Rate During Gaze to Toys	-0.407	-0.171	-0.152	0.183
Infant Voc Rate During Gaze to Face	-0.197	-0.14	-0.154	-0.054

3.3 MULTI-MODAL COORDINATION

Our next set of analyses focused on mother and infant coordination of vocalizations and gaze. Table 19 displays means and standard deviations for variables describing the coordination of infant vocalizations with mother gaze and the coordination of infant gaze with mother vocalizations, and Table 20 displays the results of HLM models for these variables.

Table 19. Means and Standard Deviations for Multi-Modal Vocalization and Gaze Coordination

			LR			HR		
		Age	N	Mean	*SD*	N	Mean	*SD*
Attention to Faces	Mother Gaze Follows Infant Vocalization	3	15	-0.55	*1.15*	5	-0.03	*0.66*
		6	14	-0.57	*0.95*	11	-0.05	*0.59*
		9	15	-1.21	*1.94*	12	-0.35	*0.66*
		12	14	-0.75	*1.26*	8	-0.94	*1.61*
	Infant Gaze Follows Mother Vocalization	3	15	1.78	*1.88*	5	1.28	*2.23*
		6	14	0.97	*2.84*	11	1.03	*1.46*
		9	15	1.25	*2.03*	12	0.81	*1.13*
		12	14	1.28	*2.08*	8	1.05	*1.6*
		3	15	2.79	*2.63*	5	0.4	*0.99*
		6	14	1.04	*1.66*	11	1.4	*1.41*
	Mother Vocalization Follows Infant Gaze	9	15	0.83	*1.69*	12	1.03	*1.35*
		12	14	2.15	*2.15*	8	1.17	*1.9*
		3	15	0.17	*1.63*	5	-0.39	*1.54*
		6	14	0.51	*0.88*	11	0.26	*0.6*
	Infant Vocalization Follows Mother Gaze	9	15	1.1	*1.78*	12	0.47	*0.83*
		12	14	1.14	*1.29*	8	0.77	*1.15*
Attention to Objects		3	15	2.47	*2.7*	5	1.74	*0.97*
		6	14	2.3	*2.72*	11	0.75	*1.73*
	Mother Gaze Follows Infant Vocalization	9	15	1.27	*2.11*	12	1.09	*1.36*
		12	14	2.59	*3.36*	8	1.89	*2.14*
		3	15	4.28	*3.07*	5	6.79	*5.07*
		6	14	3.91	*3.74*	11	4.29	*3.99*
	Infant Gaze Follows Mother Vocalization	9	15	5.75	*4.13*	12	6	*4.55*
		12	14	5.85	*2.44*	8	6.66	*5.51*
		3	15	3.46	*3.01*	5	3.96	*3.69*
		6	14	8.4	*5.16*	11	7.69	*3.4*
	Mother Vocalization Follows Infant Gaze	9	15	10	*6.74*	12	10.49	*5.04*
		12	14	9.84	*4.74*	8	11.26	*3.4*
		3	15	2.24	*2.48*	5	1.85	*1.33*
		6	14	3.98	*2.87*	11	2.4	*1.91*
	Infant Vocalization Follows Mother Gaze	9	15	3.81	*3.66*	12	2.47	*2.12*
		12	14	4.43	*3.39*	8	3.32	*3.8*

Table 20. HLM Models of Multi-Modal Vocalization and Gaze Coordination

		β	SE	t (df)	p-value
Attention to Faces					
Mother Gaze Follows Infant Vocs	Intercept, β_{00}	-0.625	0.164	-3.8 (29)	<0.001
Infant Gaze Follows Mother Vocs	Intercept, β_{00}	1.21	0.245	4.94 (29)	<0.001
Mother Vocs Follow Infant Gaze	Intercept, β_{LR0}	2.927	0.629	4.66 (28)	<0.001
	HR, β_{LR0}	-1.824	1.153	-1.58 (28)	0.125
	Linear Growth, β_{LR1}	-0.848	0.229	-3.7 (28)	<0.001
	HR, β_{HR1}	0.913	0.418	2.18 (28)	0.038
	Quadratic Growth, β_{LR2}	0.085	0.023	3.65 (28)	0.001
	HR, β_{HR2}	-0.094	0.041	-2.32 (28)	0.028
Infant Vocs Follow Mother Gaze	Intercept, β_{00}	0.083	0.2329	0.36 (29)	0.726
	Linear Growth, β_{10}	0.112	0.0393	2.85 (63)	0.006
Attention to Objects					
Mother Gaze Follows Infant Vocs	Intercept, β_{LR0}	1.79	0.273	6.56 (29)	<0.001
Infant Gaze Follows Mother Vocs	Intercept, β_{00}	5.25	0.405	12.96 (29)	<0.001
Mother Vocs Follow Infant Gaze	Intercept, β_{00}	3.658	0.742	4.93 (29)	<0.001
	Linear Growth, β_{10}	1.782	0.471	3.79 (29)	<0.001
	Quadratic Growth, β_{20}	-0.113	0.046	-2.45 (29)	0.021
Infant Vocs Follow Mother Gaze	Intercept, β_{00}	3.158	0.335	9.43 (29)	0.001

3.3.1 Gaze to Faces.

We hypothesized that both mothers and infants would follow their partner's face directed vocalizations with looks to their partner's face starting at 3 months. Contrary to our expectations, frequencies of mother gaze following infant vocalizations to mutual gaze were very rare, likely due to relatively high frequency with which mothers looked to infants' faces (making it unlikely that an infant would vocalize to mother's face at a time when mother was not already looking at infant's face). In fact, the frequency of mother gaze following infant vocalizations to mutual gaze was significantly *less* than would be expected by chance, indicating that this is a particularly uncommon method by which mothers and infants achieve mutual gaze. This circumstance never occurred in 36% of dyads at 3 months, 63% of dyads at 6 months, 80% of dyads at 9 months, and 47% of dyads at 12 months. There was no significant change over time and no Risk Status differences for this variable. Consistent with our prediction, the frequency of infant gaze following mother's vocalization to infant face was significantly greater than would be expected by chance (β_{00} = 1.21). This variable did not show significant change over time or differences by Risk Status.

With regard to vocalizations following gaze, we hypothesized that mothers would vocalize to their infant's face following an infant gaze shift to face starting at 3 months, but that infants would not show this type of coordination until later in the first year. Consistent with this hypothesis, infants did not vocalize to their mother's face within 5 seconds of a mother's gaze to their face more than would be expected by chance at 3 months. However, they showed significant linear growth over time, and were vocalizing following mother's gaze more often than would be expected by chance by 6 months, β_{00} = .41, $t(29) = 2.78$, $p = .014$. It should be noted, however, that this was still relatively rare and never occurred in 16.7% of dyads at 3 months, 46.7% of dyads at 6 months, 50% of dyads at 9 months, and 30% of dyads at 12 months.

Risk status was a significant predictor of linear and quadratic growth in the frequency of mother vocalizations following infant gaze to face. While mothers of HR and LR infants did not differ in the overall adjusted frequency of following, mothers of LR infants displayed a u-shaped pattern of growth over the first year, while HR infants displayed more linear growth. At 3 months, mothers of LR infants vocalized following infant gaze to face approximately 2.93 times more than would be expected by chance, with an initial decrease followed by significant acceleration over time such that by 12 months instantaneous linear growth was positive ($p = .007$). Mothers of HR infants, on the other hand, started off with 1.82 fewer follows on average ($p = .125$), but displayed a basically flat developmental trajectory, with almost no linear or quadratic growth.

3.3.2 Gaze to Objects.

Our next set of analyses focused on the frequency with which mothers' gaze followed infants' object directed vocalizations and infants' gaze followed mothers' object directed vocalizations (see Table 2 for a visualization of this variable). We predicted that mothers would follow their infant's vocalizations as early as 3 months, but that infants would not follow their mothers object directed vocalization until later in the first year. As can be seen in Table 20, the frequency with which both mothers and infants followed their partners' directed vocalizations with looks to that location was greater than would be expected by chance, and revealed no effects of infant age or Risk Status. In fact, counter to our expectations, infant gaze following mothers' vocalizations was more frequent (β_{00} = 5.25) than mother gaze following infant vocalizations (β_{00} = 1.79).

Next, we examined object directed vocalizations following gaze shifts to objects. Again, we hypothesized that mothers would follow infants' gaze shifts to an object with an object-directed vocalization significantly more than expected by chance at 3 months, and that infants would not be coordinated at 3 months, but would grow in coordination over time. As expected, the frequency with which mothers followed their infant's gaze shift to an object with a vocalization in the direction of that object was significantly greater than would be expected by chance at 3 months. Mothers also displayed positive, quadratic growth in this variable with a small amount of deceleration (i.e. flattening) over time. Contrary to our hypothesis, the frequency with which infants followed their mother's gaze shift to an object with a vocalization directed to that object was greater than would be expected by chance and did not show significant change over time. Mothers and infants followed their partner's gaze with vocalizations at similar rates at 3 months, but mothers increased over time such that they were following infants' gaze shifts with vocalizations approximately 10 times more than would be expected by chance at 12 months (see Table 19).

3.4 CONCURRENT RELATIONS AMONG COORDINATION VARIABLES

Our next set of analyses focused on the bivariate relations between the primary coordination composite variables at each age point (see Table 21). We hypothesized that mother-infant dyads that were more coordinated in one domain would be more coordinated in other domains as well. Contrary to our hypothesis, vocal coordination and object gaze coordination were not related at any age.

Table 21. Concurrent Relations among Coordination Variables

		Object Gaze Composite	Mutual Gaze Composite
3 months	Vocal Composite	0.01	0.14
	Object Gaze Composite		-0.11
6 months	Vocal Composite	-0.15	0.08
	Object Gaze Composite		-0.14
9 months	Vocal Composite	-0.03	0.42*
	Object Gaze Composite		-0.42*
12 months	Vocal Composite	-0.09	0.37^{o}
	Object Gaze Composite		-0.41^{o}

In fact, as can be seen in Table 21, the only significant relations between coordination variables occurred at 9 months, when greater vocal coordination was associated with greater mutual gaze coordination ($r = .42$, $p = .03$), and greater mutual gaze coordination was associated with lower object gaze coordination ($r = -.42$, $p = .029$). Similar, although non-significant, relations were apparent at 12 months (Vocal & Mutual gaze: $r = .37$, $p = .095$; Mutual Gaze & Object Gaze: $r = -.41$, $p = .06$).

3.5 LONGITUDINAL RELATIONS AMONG COORDINATION VARIABLES

Next, we analyzed how coordination variables related to each other across ages. Our first set of analyses examined how coordination within each domain related from age to age (e.g. how vocal coordination at 3 months related to vocal coordination at 6 months; see Table 22). To our surprise, neither vocal coordination nor object gaze coordination composites related from one age to the next. Only mutual gaze coordination displayed any relation across time, with 6 month mutual gaze coordination predicting 9 month mutual gaze coordination ($r = .71$, $p < .001$).

Table 22. Longitudinal Relations among Coordination Variables

	6 months	9 months	12 months
Vocal Coordination			
3 months	-0.09	-0.18	-0.15
6 months		0.12	0.01
12 months			0.17
Mutual Gaze Coordination			
3 months	-0.02	0.05	0.37
6 months		0.64**	-0.13
12 months			0.16
Object Gaze Coordination			
3 months	0.40	0.30	-0.32
6 months		0.02	0.10
12 months			0.17

Given the absence of concurrent and longitudinal relations between coordination variables, we were not surprised to find that our hypothesis that vocal coordination at 3 months would predict object gaze coordination at later ages was not supported.

3.6 EARLY COORDINATION OF GAZE AND VOCALIZATIONS PREDICTING LATER LANGUAGE

Prior to analyzing the predictive relationships between early coordination variables and later language development, we examined Risk Status differences in later language. Our dependent variable was a composite of standardized 18 and 24 month CDI and Mullen scores (Cronbach's alpha = .912). Eighteen and/or 24 month language scores were available for 23 (10 HR) of the 30 infants (1 infant did not have an 18 or 24 month visit, 6 infants have not yet turned 18 months). Although the language scores of HR infants were somewhat lower than the language scores of LR infants, in contrast with previous research our sample of HR infants did not differ significantly from the LR sample (M_{LR} = 0.19, SD = 0.80; M_{HR} = -0.22, SD = 0.88; note that these composites are standardized with a mean of 0).

Previous research has reported predictive relations between aspects of mother-infant vocal and gaze coordination and later language development. Given the unexpected results regarding the lack of developmental growth in vocal coordination as well as the absence of concurrent and predictive relations between coordination variables, the data did not provide clear indications of which coordination variables to include at which ages. Based on previous research, we decided to include coordination variables only from the second half of the first year (9 and 12 months) in this analysis, as these are the ages at which coordination has been shown to be well-established and predictive of future language (Carpenter et al., 1998; Jasnow & Feldstein, 1986; Tamis-LeMonda et al., 2001). Thus, vocal coordination composite, object gaze coordination composite, and multi-modal coordination variables at 9 and 12 months were included in this exploratory model.

We used a backwards stepwise regression to determine which variables created the best predictive model. The model begins with all candidate variables included and successively removes variables based on the significance value of the t-test for each predictor. The predictor with the lowest significance value is compared to a removal criterion (in this case $p = .10$), the predictor is removed if it meets the criterion, and the model is re-estimated with the remaining predictors. This is continued until no more variables meet the removal criterion, thus leaving only those variables that make significant contributions to explaining variance in the dependent variable. This procedure indicated that none of the measures of coordination were significant predictors of later language.

4.0 DISCUSSION

The overarching goal of this study was to describe the development of the dyadic coordination of vocalization and gaze behavior between mothers and infants over the first year of life in a group of infants at heightened vs. low risk for autism spectrum disorder. In addition to describing developmental trajectories of behavior, the study aimed to contribute to our understanding of how coordination is established and develops by investigating how measures of individual behavior and coordination related to one another within and across behavioral domains, both concurrently and across time. To our knowledge this is the first study to take a longitudinal and micro-analytic approach to the study of coordination in mother-infant interactions in the first year of life.

There were several unexpected findings, and in the sections below, I will discuss these results and their implications for how we conceptualize and study coordination in early mother-infant interactions. I will begin with a description of the findings on the development of the coordination of vocal and gaze behavior in the first year of life. This will be followed by a more extensive treatment of some of the unexpected null findings and discussion of two major conclusions from this research: first, that mother-infant interactions are bidirectional and multi-modal; and second, that coordination is impacted by the vastly changing context and dynamics of interactions across infants' first year of life.

4.1 THE DEVELOPMENT OF VOCAL AND GAZE COORDINATION IN MOTHER-INFANT DYADS

This study provides new evidence that dyadic coordination is a very early emerging phenomenon that is supported by both mothers and infants. Results relating to dyadic coordination of vocalizations indicated that mothers and infants were adjusting the timing of their vocalizations to coordinate with one another from the time infants were just 3 months old and there was little developmental change over time. Previous research has shown that mothers and infants coordinate their vocalizations with one another by the time infants are 4 months old (Beebe et al., 1988; Jaffe et al., 2001), and this study suggests an even earlier onset of coordination. Although a review of prior cross-sectional studies suggested that we may see developmental change in vocal coordination (e.g. Jaffe et al., 2001; Jasnow & Feldstein, 1986), this longitudinal study indicated that, in the context of toy play interactions, the degree to which mothers and infants coordinated the timing of their vocalizations did not show a clear developmental pattern and in some cases (e.g. coordination of latencies to respond) may have been strongest when infants were only 3 months.

There has been little previous research specifically focused on the naturalistic coordination of gaze behaviors, and no other study of the development of this coordination over time. As discussed in the introduction, most of the research on “gaze following” and “joint attention” behaviors was conducted in the context of structured, laboratory interactions focused on what infants are capable of with regard to joint attention behaviors, rather than what they actually do in naturalistic social interactions (e.g. Morales, Mundy, Delgado, Yale, Messinger, et al., 2000; Mundy, Sigman, & Kasari, 1994; Tomasello & Farrar, 1986). This study adds to the literature by providing a picture of what gaze coordination looks like in a more unstructured setting. In this context, mothers and infants achieved higher than chance levels of simultaneous attention to both objects and faces beginning as early as 3 months of age, and the amount of time spent in coordinated attention increased significantly across the first year. Just as with vocal coordination, mothers and infants appeared to be equal contributors to the creation of moments of simultaneous attention to objects.

Examination of the development of coordination of gaze to faces (mutual gaze coordination) revealed several new and intriguing findings. Although *coordination* of gaze to both objects and faces increased over time, the raw amount of time spent in simultaneous attention to faces reduced dramatically. Thus, while mothers and infants looked at one another's faces less as infants got older, they were much more likely to have those looks occur simultaneously. This is an important addition to our understanding of mutual gaze in a developmental context. A number of studies have commented on the reduction in face looking and increase in interactions with objects over time (e.g. Friedman et al., 1976; Kaye & Fogel, 1980), but few have examined how mothers and infants are timing looks to faces with their partner. While our research confirmed that joint interactions with objects became a larger part of mother-infant interactions across the first year, the finding that mothers and infants increase the chance level recurrence of looks to one another's faces over time suggests that moments of face-to-face interaction remain a significant part of these social experiences.

The picture for leading and following in mutual gaze coordination was different than that for coordination of attention to objects. Mothers rarely followed infants into moments of mutual gaze, and in fact the frequency of mother following infant to mutual gaze was negatively correlated with other measures of mutual gaze coordination. This is likely a reflection of the differences between mothers' and infants' overall looking to faces. Although mothers decreased the amount of time they spent looking to infants' faces between 3 and 12 months, they spent much more time looking to infants' faces than infants spent looking to mothers' faces at all four time points. Observationally, mothers interspersed interactions with and looks to toys with frequent quick glances to their infants' faces and shifted their gaze back and forth between infant's face and toys frequently, particularly at later months. Infants, on the other hand, rarely looked to their mothers' faces after 3 months. These patterns of behavior made it unlikely that an infant would lead in the onset of a moment of mutual gaze by looking to his/her mother's face at a moment when mother was not already looking to infant's face. The consequence of this pattern of interaction is that nearly every time infants looked to their mothers' face, mothers were already looking at them. Consistent with findings from Yu and Smith (2013), who reported that 12 month-old infants rarely looked to their mothers' faces during toy play interactions, this study provides further evidence that in naturalistic interactions infants seldom use looks to their mother's face as a method of gaze following. Instead, these moments of coordinated gaze to face likely serve other purposes, such as checking for reactions or sharing affective responses (Mundy et al., 2007; Yale, Messinger, Cobo-Lewis, & Delgado, 2003).

Findings on the development of the coordination of face-directed vocalizations with partner gaze to face mirrored these findings for mutual gaze coordination. Infants followed mother vocalizations to mutual gaze more than would be expected by chance at 3 months with little developmental change, however infants rarely led in moments of mutual gaze, so the frequency of mothers following infant vocalizations to mutual gaze was very low. When infants shifted their gaze to mother's face, mothers followed with a vocalization more often than would be expected by chance, but they did so relatively infrequently overall (see Table 19). And although there was an increase in the frequency with which infants vocalized to mother's face following mother's gaze shift to infant's face, this did not exceed chance levels at 3 months, and it remained rare across the first year.

Multimodal coordination during gaze to objects was much more frequent than multimodal coordination of gaze to faces. Both mothers and infants adjusted their gaze contingent upon their partner's vocalizations *and* timed their vocalizations with their partner's gaze shifts starting as early as 3 months. However, mothers and infants displayed somewhat different patterns in terms of the frequency and development of these contingent interactions, indicating that they may be using multi-modal coordinations in different ways. Specifically, the adjusted frequency with which infant gaze followed the direction of mother vocalizations was substantially higher than the frequency with which mother gaze followed the direction of infant vocalizations. Infants appeared to be using mothers' directed vocalizations as a pathway to simultaneous attention to objects, while mothers, whose relative height gives them a more global view of the entire interaction and easy access to attend frequently to their infants' faces, were less reliant on infant vocalizations in coordinating gaze to objects.

For their part, between 3 and 12 months mothers increased the frequency with which they vocalized in the direction of an object following an infant gaze shift to that object; but this developmental change was not paralleled by infants. Thus, while mothers and infants looked similar in this behavior at 3 months, infants used this type of response much less than mothers by 6 months and beyond. Maternal vocal responses to infants' gaze shifts may become especially important as infants begin developing language, as they create opportunities for mothers to provide labels or descriptors of the object of infants' focus (Gros-Louis et al., 2006).

Overall, this longitudinal investigation of dyadic coordination of vocalizations and gaze across the first year revealed that mother-infant interactions take on a coordinated structure beginning in the first months of infants' lives and while coordination of gaze to face and coordination of gaze to objects increased significantly from 3 to 12 months, vocal coordination did not show developmental change over time. Furthermore, mothers and infants were both active contributors to the coordination of vocalizations and gaze, however results related to mutual gaze coordination and multi-modal coordination suggested that they may rely on different aspects of one another's behavior to create moments of shared attention. The developmental picture outlined here is best understood in light of the vastly changing content and dynamics of the parent-infant interaction over the course of the first year. The ways in which changes in the overall features of mother-infant interactions may impact development of dyadic coordination will be discussed further below.

4.2 LACK OF RISK STATUS DIFFERENCES

Previous research on infants at heightened risk for ASD revealed a number of subtle delays in the development of vocal and gaze behaviors that we believed could have implications for how mothers and infants coordinated these behaviors (e.g. Bedford et al., 2012; Ibanez et al., 2008; Paul et al., 2011). In contrast to our expectations, we found very few differences between dyads with HR and LR infants in production or coordination of vocalization and gaze behaviors. In fact, one of the most prominent Risk Status difference findings, that HR infants had faster growth in consonant production that LR infants, was in the opposite direction of what was hypothesized, and in direct contradiction with some previous research (e.g. Paul et al., 2011).

One explanation for this unexpected result may come from the size and composition of this particular sample. One of the most consistent findings with regard to HR infants is the high degree of variability in development. While it is the case that HR infants are at heightened risk for developmental delays, a majority of HR infants will develop completely typically (Ozonoff et al., 2014). It is notable that the sample of HR infants that we observed did not exhibit delayed language based on available standardized language assessments at 18 and/or 24 months; their performance was similar to that of the LR comparison group. Furthermore, of the 9 HR infants in this sample who have reached 18 months, none have failed the Modified Checklist for Autism in Toddlers (MCHAT-R/F), a validated developmental screening tool for autism risk (Robins et al., 2014). Thus, it may simply be the case that this sample includes HR infants who are developing relatively typically. When all of the infants in this study have reached 36 months and completed outcome assessments, it will be possible to examine differences between infants who have significant language delays, infants who may develop ASD, and infants who are typically developing. As it stands, it may be that the group of infants who are delayed or atypically developing is too small to impact group level differences.

It is also important to note that the majority of studies that have examined LR and HR infants before 12 months of age have not found differences at these early ages, even among children who go on to have ASD (see Jones et al., 2014 for a review). Although we expected that examining dyadic behavior might reveal more subtle differences that are missed when examining only the behavior of individual participants, it may be the case that HR infants are not developing all that differently from LR infants in these early months. Of course, this is a single study with a small sample of HR infants, and therefore replication is necessary with a larger (and potentially more variable) sample.

4.3 LACK OF RELATIONS TO LATER LANGUAGE

Based on theory and previous research, it was expected that the coordination of the timing of vocalization and gaze behaviors in mother-infant interactions would create structure and increase predictability in an otherwise complex interaction, features that would facilitate learning from social partners over time and thus have longer term impacts on development. In contrast with a number of studies that have reported predictive relationships between early parent and infant coordination behaviors and later language (Morales, Mundy, Delgado, Yale, Messinger, et al., 2000; Tamis-LeMonda et al., 2001; Tomasello & Farrar, 1986), we did not find that vocal or gaze coordination significantly predicted variability in language in the second year. There are at least three possible reasons for this discrepancy.

One has to do with the length of the interaction that was coded. Although selecting only 5 minutes of the interaction allowed us to code behaviors on a moment-to-moment basis at four time points in detail, something that would have been exceptionally time-consuming with a longer segment, a short interaction may not be sufficient to capture variability in mother and infant behavior that is predictive of later development. A number of studies that have previously reported relations between aspects of mother-infant interactions and later language have used interactions that lasted between 10 and 30 minutes (Carpenter et al., 1998; Tamis-LeMonda et al., 2001; Wu & Gros-Louis, 2014).

Second, unlike previous research that has examined the relation between constructs such as "maternal responsiveness" and later language, this study was focused specifically on the *timing* of behaviors in the dyadic context rather than on the content of the behavior. For example, Tamis-LeMonda et al. (2001) defined a maternal response as "a positive and meaningful change in the mother's behavior that was contiguous and contingent on the child's act". This definition of contingency is much broader than our own definitions, which related only to the timing of behaviors in relation to one another. Other studies have focused on the content of mothers' responsiveness, and the match between the content and the infants' attention (Akhtar et al., 1991; Tomasello & Farrar, 1986). While the coordination of the timing of communicative behaviors may be an important characteristic of early development, additional contextual features may also be a necessary component of the relationship between parent-infant interactions and later language development. Moving forward, coding additional content cues surrounding moments of contingency and simultaneous attention (e.g., by coding maternal speech) may be required in order to identify predictors of later language.

Third, it is possible that the variables analyzed here, focusing as they do on the timing of behaviors rather than their content or context, may be more strongly related to more basic aspects of cognitive development rather than to the development of language specifically. For example, Jaffe et al. (2001), who studied vocal coordination in interactions between 4 month-old infants and their mothers using a number of measures similar to those used here, argued that sensitivity to the timing of behaviors in social interactions should relate specifically to cognitive development. This is based on the theory that the ability to recognize regularities and contingencies in the environment is a basic cognitive skill that has implications for a number of skills important for learning. Infants who recognize and adjust their behavior based on their parent's contingent behaviors would be likely to recognize regularities in many aspects of their environment and therefore act in ways that increase learning opportunities. Jaffe et al. (2001) reported a positive relation between vocal coordination at 4 months and 12 month scores on the Bayley Scales of Infant Development-Mental Development Index.

My own research on contingency learning in a non-social context provides some further support for the view that recognizing and acting on contingencies in the environment relates to later cognitive abilities. In a study of response to changing contingencies in interactions with a rattle, I found that the degree to which 10-month-old infants adjusted their behavior with a rattle based on their expectations about the contingencies between their own actions and the rattle was predictive of later cognitive development (Northrup, Libertus, & Iverson, 2017). Specifically, infants who showed a stronger "extinction burst", or increase in rattle shaking, when the contingency between rattle and sound was removed, had higher cognitive scores in toddlerhood. It may be the case that while language development is supported by more specific, content-laden social interactions (e.g. maternal labeling during moments of joint attention), the ability to time one's behavior with a social partner is a more general cognitive skill reflecting an ability to perceive contingencies and regularities in the environment and interact effectively.

Finally, this research did not replicate a finding from my prior work with a different sample that utilized a similar measure, similar length of toy play interaction, and similar population. In a study of 9 month old infants and their mothers playing with toys at their own homes, we found that that vocal coordination, and specifically the degree to which mothers and infants matched in their latencies to respond, was predictive of later language (a composite of 18, 24, and 36 month CDI and MSEL Receptive and Expressive Language Scores) among HR infants (Northrup & Iverson, 2015). The most notable differences between the two studies are that, at this time, the longitudinal study from which the present sample was recruited is still ongoing. There are 18 month language scores for 22 infants (9 HR), 24 month language scores for 20 infants (8 HR), but as yet very little 36 month outcome data. The present study also has a smaller HR group with better and less variable language (at least based on assessments administered thus far) than that of the HR infants in the published work.

While the failure to find risk status differences or relations to later language was surprising, the results from this research have implications for how we conceptualize the development of early mother-infant interactions across the first year. In the next sections, I turn to a discussion of two major themes that emerged from this research: a) that coordination in mother-infant interactions is inherently bidirectional and multimodal, and that individual behaviors are best understood in relation to the larger interaction; and b) that coordination is a feature of the emerging developmental context, which changes drastically over the course of the first year.

4.4 MOTHER-INFANT COORDINATION IS BIDIRECTIONAL AND MULTI-MODAL

Aims 3, 4, and 5 of this study focused on how different measures of coordination related to one another, how coordination was related to individual mother and infant vocal and gaze behaviors, and how mothers and infants coordinated their vocal behaviors with their partner's gaze behaviors. Our hypotheses for these aims were based on the idea that coordination in mother-infant interactions is inherently bidirectional and multi-modal, emerging as an interaction between multiple aspects of mother and infant behavior. Below, we discuss results suggesting that a) mother and infant behavior is mutually influential and b) that this bi-directionality occurs across modalities. These findings emphasize the importance of situating infant and mother behavior in the context of the dyadic interaction.

Consistent with previous research demonstrating that mothers with greater and faster responsiveness tend to have infants with greater and faster responsiveness (Jaffe et al., 2001; Van Egeren et al., 2001), we found that for vocal coordination and object gaze coordination, measures of infant leading/mother following were related to measures of mother leading/infant following. This relation suggests that understanding coordinated interactions requires consideration of both mother and infant behavior. It is also consistent with the view that coordinated interactions are indicative of the creation of structure and predictability in the dyad. The fact that, within dyads, mothers and infants appeared to match in the degree and speed with which they respond suggests that both members are attuned to their partner's patterns of behavior and are also timing their own behavior in predictable ways.

Not only were mother and infant leading/following behaviors related within dyads, but overall, mothers and infants were equal contributors to the dyadic coordination of vocalizations and gaze to objects, with recurrence rates and frequencies of mother following infant being quite similar to those for infants following mothers. This equality in leading and following in vocal exchanges and simultaneous attention to objects began early and was generally consistent across ages. Although we were somewhat surprised to find that infants led and followed mothers equally as early as 3 months, the finding fits with a transactional model of coordination that emphasizes the bidirectional nature of parent and infant behavior (Sameroff, 2009). Rather than responsiveness being a feature of the infant or mother, it is dyadic. This view helps to explain why we see change over time in mother following infant in gaze coordination—rather than reflecting improvement in mother's ability to follow gaze, the change in maternal following is a reflection of change in the infant's behavior. Over time infants develop more sophisticated methods of directing mother attention, such as reaching for and vocalizing at objects, and this in turn creates richer opportunities for mothers to follow infant gaze. An individual's level of responsiveness cannot be understood outside the context of partner behavior, a notion that was supported not only within behavior modalities, but also across modalities.

The importance of the interaction between vocalization and gaze behaviors was supported by our analyses of multi-modal coordination as well as the relations between coordination of behaviors in one modality with individual behaviors in the other modality. As noted above, as early as 3 months, both mothers and infants adjusted their gaze to objects contingent upon their partner's vocalizations *and* timed their vocalizations with their partner's gaze shifts to objects. While there is value in understanding how mothers and infants coordinate within a single modality, these findings are a reminder that coordination is achieved through multiple pathways.

The value of considering coordination in a multimodal context was also evident in our finding that coordination of behaviors was related to production of individual behaviors across modalities. These multi-modal relations were apparent for both vocal and gaze coordination. For example, at 9 months vocal coordination was positively related to the relative frequency of mother vocalizations directed at both a toy and infant's face (within the same vocalization), but negatively related to vocalizations directed at toys only. This suggests that vocal coordination is supported by mothers shifting their gaze between objects and their infants' face but may be hindered when mothers direct most of their vocalizations at toys only. With regard to mutual gaze coordination, at 9 months dyads with infants who vocalized more during gaze to mother's face also had more mutual gaze coordination, and at 12 months dyads with mothers who vocalized more during gaze to infant face had more mutual gaze coordination. These results underscore the mutually influential and interactive nature of vocalization and gaze behavior and coordination in the second half of the first year.

Had we examined only mother *or* infant behavior, or only the coordination of behavior in one modality (e.g., gaze alone), a different picture might have emerged from this research. The bidirectional and multi-modal relations revealed here make clear that concepts like "maternal responsiveness" are not individual features of mothers, but emerge out of the dyadic interaction. Infant behavior is both impacted by and impacts how responsive mothers are, and it does so across modalities. Thus, when we consider individual behavior in the dyad, it is also important to consider how partner behavior impacts the interaction. This notion of coordination emerging as a complex interaction between multiple aspects of mother and infant behavior is even more significant when considered in the developmental context.

4.5 COORDINATION AS A FEATURE OF THE EMERGING DEVELOPMENTAL CONTEXT

Watching videos of mothers and infants interact across the first year of life, it was impossible not to be struck by the degree to which infants' development transformed the interaction from one age to the next. At 3 months, infants could do little more than react or respond to what was presented to them. They lacked the motor skills to introduce objects into the interaction or to initiate a shift in focus. Mothers, therefore, scaffolded these early interactions to fit their infants' developmental abilities, so toy play interactions between mothers and infants at 3 months typically involved interacting with no toys (just face-to-face) or only one toy at a time, making it easier to achieve periods of simultaneous attention to faces and objects. In this stripped-down context with few competing stimuli, coordination becomes a relatively simple task.

Over the next 9 months, infants gained the ability to sit, to reach for and grasp objects in their environment, and eventually to locomote independently. With the development of each of these new skills, the interactions between mothers and infants changed dramatically. As infants gained greater autonomy in their interactions with toys and objects in their environment, the interaction increased in complexity, moving from largely dyadic (mother and infant) to primarily triadic (mother, infant, and toys). Infants shifted their gaze more frequently as they got older, and mothers adjusted their behavior to match. With the ability to locomote, infants were no longer constrained to interacting with what was directly in front of them and had the opportunity to direct the interaction to new and distal objects in the environment.

A study by Van Egeren et al. (2001) that examined how "micro-contexts" (e.g. object exploration, mutual gaze) impacted mother and infant responsiveness during toy play interactions provides a framework for understanding how these shifts in infant ability and attention may impact coordination. They found that both mothers and infants were less contingently responsive to their partners during periods of infant object exploration than outside those periods. The authors interpreted this finding as an indication that, during object play, mothers and infants attend to objects at the expense of other attentional demands. While this study focused on only one time point, it has implications for how the changing dynamics in mother-infant interactions impact the attentional demands placed on both infants and mothers.

The research reported here builds on these findings by providing a longitudinal picture of how the context of mother-infant interactions might impact coordination. In particular, our findings with regard to the relations between coordination of vocalizations and coordination of gaze, the lack of development in vocal coordination, and the changing relations between individual behaviors and the coordination of behaviors, all lend support to the notion that coordination emerges out of the structure and dynamics of the interaction and is therefore neither simply a trait of the dyad nor consistent across time.

While we originally expected that relations between coordination in different modalities and across ages would be positive, as though "coordination" were primarily a feature of the dyad that would influence both domains and be predictive from one age to the next, the data suggest that these relations vary across time and reflect changes in the structure of the interaction. For example, while coordination of vocalizations and coordination of gaze were not related at 3 or 6 months, in the second half of the first year, mutual gaze coordination was positively related to vocal coordination and negatively related to object gaze coordination. In other words, dyads that had more coordination of gaze to one another's faces were also more likely to adjust the timing of their vocalizations with one another and had less coordination of gaze to objects. This result is consistent with the idea that, as infants get older and acquire motor skills that allow them more freedom to direct the interaction, there may be tradeoffs between face-to-face and vocal interactions versus object interactions.

Similarly, in the context of the changing structure of mother-infant interactions, the "lack" of a developmental trend in the coordination of vocalizations could be seen as a reflection of development in other areas. At 3 months, when interactions have a large face-to-face component and there are fewer stimuli competing for attention, both mothers and infants may have been devoting more of their attention to their partners' vocal behaviors rather than other aspects of the environment. As the interactions became more triadic, vocalization timing was likely driven by more than just the timing of a partner's vocalizations, but also by the infant's emerging skills and by other features of the interaction and environment. For example, we saw an increase in maternal vocal responses to infant gaze shifts over time, suggesting that as infants get older, mothers increasingly time their vocalizations not only with infant vocal behavior but also with their gaze behavior.

The impact of infant development on the nature of the interaction, and therefore the coordination of behaviors, was also apparent in the changing relations between coordination and individual vocal and gaze behaviors with infant age. While some relations were consistent (i.e. the relation between frequency of mother and infant vocalizations and vocal coordination), the majority were not. For example, the relation between infant production of consonant sounds and vocal coordination was only apparent at 6 and 9 months, ages when consonant sounds are first developing and being refined, and was no longer significant at 12 months when consonant sounds were common and infants are likely beginning to produce their first words (Oller, 2000). Thus, the aspects of infants' vocal production that impact vocal coordination were not a constant feature of the interaction, but changed over time as infants developed and refined new skills.

The relation between object gaze coordination and individual gaze behaviors also changed with infant age. At 3 months, object gaze coordination was related to the frequency and duration of mothers' gaze shifts, but not to infant gaze shifting behavior. Dyads with mothers who shifted their gaze more frequently and had shorter gaze durations had better coordination of gaze to objects. At this age, when mothers and infants tended to interact with only one toy at a time, mothers who shifted their gaze more frequently were likely to be doing so between their infant's face and the toy with which they were interacting, giving them frequent opportunities to check on their infant's attentional state and adjust their behavior to their infant's signals.

At 6 and 9 months, mother's gaze behavior was no longer related to coordination of gaze to objects, and instead *infant* frequency and duration of gaze shifts were related to coordination. Dyads with infants with *fewer* gaze shifts and *longer* gaze durations had more coordination of gaze to objects at these ages. Thus, as infants begin to take a more active role in directing the interaction and engaging with objects, the frequency and length of their gaze shifts takes on greater importance. It is likely that infants who shift their gaze frequently are both harder to follow and less likely to be attending to their mother's gaze.

Interestingly, relations between infant gaze behavior and mutual gaze coordination (i.e. coordination of gaze to faces) showed the opposite pattern to relations with coordination of gaze to objects, providing further evidence that there are tradeoffs between coordination of gaze to objects and coordination of gaze to faces. At 6, 9 and 12 months, dyads with infants with *more* gaze shifts and *shorter* gaze durations had better coordination of gaze to faces. Thus, infants who shifted their gaze frequently between objects and their mother's face may have engaged in a higher degree of face-to-face coordination with their mothers, but potentially at the expense of interactions with toys.

The lack of longitudinal studies in the field has limited our understanding of how coordination in mother-infant interactions develops over time. An underlying assumption of a number of theoretical and empirical models of early mother-infant coordination has been that the ability to coordinate with a communicative partner is an individual trait that will be predictive across domains and ages, and will relate to future development (Bigelow et al., 2010; Feldman, 2007; Tamis-LeMonda et al., 2001). The research presented here offers a challenge to this view. We did not find that coordination at one age predicted coordination at the next, nor were the relations between coordination in different behavioral domains straightforward and positive. Instead, the relations between coordination variables within and across ages suggest that the task of and pathways to achieving coordination in mother-infant interactions changes with infant age and developmental level.

4.6 GENERAL CONCLUSIONS AND DIRECTIONS FOR FUTURE RESEARCH

Taken together findings from this longitudinal study of the coordination of mother and infant vocal and gaze behaviors across the first year of life paints a complex picture of how dyadic gaze and vocal coordination develop. Results indicated that the coordination of the timing of vocalization and gaze behaviors is early emerging and supported by both mother and infant behavior, but that relations between coordination across domains and ages is not straightforward. Rather than coordination emerging due to individual characteristics of mothers and infants within dyads, the findings suggest that coordination emerges as a feature of the larger interaction between infant developmental ability and behavior, mother behavior, and the overarching context of the interaction. While a number of researchers have discussed the bidirectional, multimodal nature of mother-infant coordination (Feldman, 2007; Trevarthen & Aitken, 2001; Van Egeren et al., 2001), few have examined how these processes change with infant age and developmental level. The results presented here underscore the importance of understanding mother and infant behavior during social interactions as transactional and multi-modal, and also provide new evidence that coordination of behaviors does not develop in a simple, linear fashion driven primarily by parent and infant traits.

The surprising nature of some of these results suggests a number of areas for future research into the dynamics of mother-infant interactions across the first year. First, coding these interactions made apparent the importance of infant motor development in how social interactions are structured. Examining how infant posture, locomotion, and the development of reaching skills relate to mother and infant coordination of behaviors may help to clarify some of the results reported here. In particular, it would be useful to examine differences in coordination between infants of the same age (e.g. 6 month olds) who were sitting independently and those who were not. This would provide us with further evidence that individual and coordination behaviors are driven at least in part by motor skill development and the new opportunities that they afford for interaction.

Second, as infants get older, the relations between coordination in different domains becomes more complex. Specifically, results suggest that there may be tradeoffs between face-to-face interactions, which are supportive of vocal coordination, and object interactions. Using a framework similar to that of Van Egeren et al. (2001), these results could be further probed by examining coordination during different "micro-contexts" within interactions (e.g., comparing vocal coordination during face-to-face gaze vs. moments of simultaneous attention to objects vs. moments of uncoordinated gaze). Conducted longitudinally, we would hypothesize that changing micro-contexts within the interaction would also relate to changes in coordination.

Finally, the rich dataset collected for this research lends itself to some additional questions regarding particular types of interactions considered important for development. As mentioned previously, the relation between early parent-infant interactions and later language development may be dependent on particular types of interactions, such as maternal labeling in moments of simultaneous attention, and thus the coding of the content of maternal speech may provide meaningful information on the development of the content of maternal responses. Similarly, with regard to gaze coordination, the development of joint attention, or simultaneous attention to both mother's face and objects, is a key developmental milestone (Corkum & Moore, 1998; Moore & Dunham, 2014; Mundy et al., 2007). Examining how early coordination of gaze behaviors relates to the onset of this more advanced skill could add to our understanding of early development.

As the literature review in the introduction to this paper makes clear, the vast majority of research on the coordination of the timing of vocal and gaze behaviors in caregiver- infant interactions has focused on a single member of the dyad, examined only one time point, and/or only one modality of behavior at a time. Taken together, the results of this longitudinal research indicate that studying the dynamics of coordination in these ways oversimplifies a complex, bidirectional, multimodal process that changes with infants' age and developmental abilities. The more that we can continue to probe how infants develop in this complex context, the better we will be able to understand how disruptions in the process may occur, and how they may be remediated.

APPENDIX A

GAZE & VOCALIZATION CODING MANUALS

Gaze Coding Manual

Code all instances in which the individual's eye gaze is directed toward either another person or an object in view of the camera.

- Coding should begin on the first frame where the individual is clearly looking to the object/person and end on the last frame before they shift their gaze.
  - Note: this means there will often be gaps between codes for when gaze is shifting (or if an individual blinks during a gaze shift), or for times when gaze is unclear or directed at something other than an object, the camera, or the partner. See below for how to code these "uncodable" moments.
- NOTE: individual's gaze must pause at least briefly in order for gaze to be coded.
- If individual blinks but continues to look at the same location**, do not stop** coding during the blink.
- If individual blinks and changes gaze before and after blink, **do not code** gaze during the blink.
- Sometimes infant gaze will lag behind as they follow a moving object. If they move their eyes in the direction the object is moving and fixate on the object when it becomes still, code the entire duration as a look to that object.
- If infant is blinking frequently (e.g. due to banging objects), but looking in the direction of the toy, you can keep coding attention to the object. This also applies if infant brings object very close to face to view them and isn't focused directly on them (added 5/31).
- If eye gaze is somewhat unclear, you can use contextual cues to make a decision about where a person is looking (e.g. if they are reaching for something, but you can't see their eyes perfectly, you can assume they are looking at the thing they are reaching for).
- If the object of eye gaze is outside of the frame, you can try to figure out what the object is by using either sounds or waiting to see if the object comes into view at a different time.
- Pay careful attention to any movement of the eyelids when looking for gaze shifts.
- If you cannot tell what the individual is looking at, code nothing (NOTE: this is not the same as being able to tell that they are looking at a toy, but not being able to identify what the toy is. In the case that you can tell they are looking at a toy, but can't identify the toy, code gaze to object and "Unclear Object" as outlined below).
- 2/28/17: For mom gaze, in instances where my picks up and object, shifts gaze to where she's going to place the object and immediately puts the object there (so it comes in her gaze again), continue the code.

Mother/Infant Gaze Tier:

Gaze to Partner: Use this code when the person is gazing at their partner's face.

Gaze to Object: Use this code anytime the person is gazing to a toy. Create a new annotation each time the individual shifts gaze to another location.

- In instances when it is impossible to tell whether the individual is looking at the partner's face or a toy (e.g. coding infant gaze when mom is holding a toy in front of her face, coding mother gaze when mom is holding a toy in front of baby's face), code gaze to "Partner's Face".
  - NOTE: As of 2/27/2016—you should only use this code in instances where the object is directly in front of the partners face. Do not use when baby is mouthing the object. If mom is looking through the ring at baby's face, mom gaze should be "partner's face" and baby's gaze should be "face-object". If mom is holding a ring halfway between her face and baby's face and looking through the ring to baby's face, just code "partner's face". The ring needs to be right in front of baby's face in order to code "face-object".
  - IN ADDITION:
    - For the duration of the time that the individual is looking to both the object and the face, select the appropriate code on the Mother/Infant gaze location tier.
      - For example, if you have coded gaze to "Partner's Face" above, then also code the toy on the gaze location tier. Fill in the rest of the gaze location tier with the code for "face".
  - ALWAYS also code this situation on the face/object tier as well, to note that this situation occurred.

Gaze to Camera: Use this code if the person is clearly looking to either the camera or the camera person. If their gaze is shifting between the camera and camera person you only have to code one gaze.

Identifying Object of Gaze:

- Identify what object the person is looking to using the manual described below (26 options).
- NOTE: If you can't tell what shape a small object is but can see the color, code the lowest number within that color (i.e. highest on the list).
  - NOTE: Combinations of toys
    - If there are multiple objects in the person's view (e.g. mom is putting rings onto stand and looking at the ring toy), code according to rules outlined here.
    - If individual is looking at a combination of small toys (e.g. yellow and pink ring) or objects from separate toys (e.g. the duck head and the green half) code the lowest # item (i.e. closest to top of list).
      - E.g. If individual is looking to pink ring (3f) and yellow ring (3g), code pink ring (3f). If individual is looking to duck head (3a) inside green half (4a), code the duck head (3a).
      - If infant is looking at a big pile of the small shapes and you can't see precisely which objects are in the group, just code the highest one (i.e. red circle).

- NOTE: Changing Combinations of Toys
    - In instances when there are changing combinations of toys but the individual's gaze does not shift (e.g. infant is looking at the ring toy and then takes the duck head off the toy and continues to look at the duck head in a different location) you should make one code on the "gaze" tier (i.e. "infant gaze"/ "mother gaze") and make two separate codes on the "gaze location" tier that reflect the shift on what toy the individual is specifically looking at (e.g. from "ring toy" to "duck head").
        - In order to make multiple annotations on the "gaze location" tier, you will first have to make a big annotation, and then right click on the annotation and choose "New annotation after" (you can also highlight the annotation and press Alt-Shift-N). This will split the annotation into two. You can then adjust the point of change by holding the Alt key and hovering your mouse over the split in the annotation. An arrow will show up and you can then drag the shift to the appropriate location.
        - The shift from a larger toy to a smaller toy (e.g. from ring toy to duck head) should be made at the point that the smaller object becomes separate from the larger object. Similarly, the shift from a smaller toy to a larger toy should be made at the point where the smaller object makes contact with the larger object.
        - If an infant is banging two objects together, code them according to the combination of objects rules (below) but don't worry about capturing every little gaze shift that occurs during banging.

Coding "Uncodable" Moments

- Code Uncoded sections of time if they last longer than 500 ms (not including gaze shifts).
    - Unclear: Use this in instances where it is just too hard to tell what the person is looking at
    - Off Camera: Use this for when the individual looks at something that is off camera
    - Poor video angle/quality: Use this for instances where you can't tell where the person is looking because you cannot see their eyes well enough due to a problem with camera angle or quality.
    - Eyes Closed
    - Crying
    - Unfocused Gaze
    - Other: When you use this code, please make a comment on the "comment tier" with a short description of why you have not coded.
    - Self/Clothes/Hands
    - Partner Body/Hands

<u>Objects Key:</u>

0. Bag of Toys: Use this code if individual is looking into the bag of toys or at the outside of the bag.
1. Rattle
2. Book

3. Ring Toy (code if individual is looking at any combination that includes the stand, with or without rings/duck head; includes stand by itself)
    3a. Duck head
    3b. Dark blue ring
    3c. Orange ring
    3d. Green ring
    3e. Pink ring
    3f. Yellow ring
    3g. Light blue ring
4. Whole Spherical Puzzle (code if individual is looking to any combination of blue and green half, with or without shapes)
    4a. Green Half (code if individual is looking to any combination of green half and shapes)
    4b. Blue Half (code if individual is looking to any combination of blue half and shapes)
    4c. red circle 
    4d. blue square 
    4e. yellow oval 
    4f. orange rectangle 
    4g. purple pentagon 
    4h. orange star 
    4i. green polygon 
    4j. red moon 
    4k. yellow equilateral triangle 
    4l. purple half circle 
    4m. green obtuse triangle 
    4n. yellow octagon 
5. Unclear Object: Use this code when you can tell the individual is looking at one of the toys, but the object is not in view of the camera (NOTE: don't use this code for instances when you just can't tell where they are looking, only for instances when you can tell they are looking at something, but can't see that thing).
6. Face: Use this code in instances when the individual is looking to the person's face and an object comes into view. In this case you will code Face on the main tier, and code the appropriate object code on the gaze location tier during instances when the object is in view. You will put this "Face code" in the rest of the time (when the infant is just looking at the person's face).

Vocalization Identification Coding Manual

Infant Vocalizations

Vocalization: An infant vocalization is any sound produced by the infant. This includes all babbles, vocalizations, fusses, cries, and vegetative sounds.

- For a vocalization to end, the speaker must either stop vocalizing for at least .5 seconds or *take a breath*. Some speakers pause in between their vocalizations without taking a breath in between. In these instances, if the pause is less than .5 seconds, code all sounds produced as a single vocalization.
  - If the infant takes a voiced inhale without a pause you should not create a new vocalization.
  - Exception: If the infant is crying or fussing you do not need to make a new voc with every inhale, only if there is >.5 second pause.
- Sometimes babies make sounds with objects such as toys or hands in the mouth. These vocalizations should be coded.
- Vocalizations *can* occur in whisper form. These vocalizations should be coded. Do not confused deep breaths with whispers. *Deep breaths are not coded.*
  - Whispers can be distinguished from exhales based on length and the presence of consonant like sounds.
    - NOTE: H sounds do not count as consonant sounds for our purposes.
    - If baby makes an unvoice consonant sound (e.g. "t", "d", "p", without any voicing or whispered vowel sounds after, don't code.
  - Sometimes infants will make sounds when they breath because they are congested- these should not be coded as vocalizations.
    - This is also true for the purposes of splitting—you should still split on the breath, even if it's congested.
  - Don't code unvoiced breath noises like sighs or exhales that don't include voicing, even if they are a part of a voc that includes voicing. This includes when they get excited and have quick sharp inhales and exhales- don't code if not voiced.
- NOTE: Don't code the kind of automatic mouth sounds that are made when the baby moves his mouth on a toy or smacks his lips etc., unless they occur with some kind of voiced exhalation.
- NOTE: Don't code the very short sounds infants make when they force air out quickly and make a sound in back of their throat. You should take length of voc into account here. If they make a forced sound in back of throat for extended time, you should still code.
  - HOWEVER: Include small sounds within a voc (even if you might not otherwise code them) if they occur in the pause between two bigger sounds. In other words, don't split unless the pause is actual silence.
- NOTE: If you're not pretty sure it's the baby making the sound, don't code it.
- The vocalizations can be categorized in 1 of 2 ways:
  - **Voluntary**: Any vocalization made voluntarily. This includes affective vocalizations like fusses and cries and playful vocalizations like squeals, gasps, animal noises, etc.
  - **Involuntary**: Burp, Cough, Sneeze, etc. (same as adults make)
    - Don't code hiccups, however if the sound is pretty loud and noticeable and a mix between a burp and a hiccup, code it. (decision made 7/19/2016)

- NOTE: If an involuntary voc is right next to a voluntary voc (without a 500ms pause or breath), still split them up.

Caregiver Vocalization

- Vocalization: Any voluntary sound produced by the caregiver.
  - For a vocalization to end, the caregiver must either stop vocalizing for at least .5 seconds or take a (silent) breath.
    - Make sure to capture entire vocalization before checking for pauses (particularly in instances with trailing sounds at the end or hard consonants that are difficult to hear outside the context of the full word).
    - Do not code inhale sounds that do not contain voicing, however do code voiced inhale sounds (such as gasps)
      - If the caregiver does a voiced inhale (such as a gasp) without a pause you should not create a new vocalization.
    - Do code unvoiced exhale sounds that are very dramatic/clearly intentional (like whispers or "vortex sound")
    - Do code non-speech playful sounds like snorts, whistles, vortex noises
    - If sound cuts out and there is no back up, you can use lip reading to finish out voc you heard the beginning of, but don't code vocalizations that occur entirely during silence.
    - Laughter: There has to be voicing in order to code laughter from mom. If there is any voicing, code the whole laugh (including unvoiced parts).

APPENDIX B

ESTABLISHING RANDOMIZED BASELINES

Randomized baselines for measures of coordination were quantified using R statistical programming software. The purpose of these randomized baselines was to provide a reference for the likelihood of coordination by chance. Functions were written to take raw streams of data and randomize the order of events using the following method:

1. Coded data for each infant and each behavior was organized into individual dataframes with each row of data corresponding to a single behavioral event (e.g. vocalization, gaze to parent, gaze to object) with columns indicating start time, end time, and a code for the behavior (e.g. a number corresponding to the gaze location).
2. A column was added to all dataframes indicating the “time to the next event” (i.e. pauses in the case of vocalizations, periods of looking away from either partner or toys in the case of gaze).
3. Using the “sample” function in R, the order of these events were randomly sampled 500 times. The order of event durations and “time to the next event” were randomized separately so as to randomize both the order of events and the order of “pause” durations or time between events. New start and end times were then created using the event durations and time to next codes. (https://www.rdocumentation.org/packages/base/versions/3.5.0/topics/sample)

4. Each of the 500 shuffled data frames for each variable for each partner in the interaction were saved and used to calculate shuffled coordination variables (i.e. all coordination variables were calculated 500 times). For example, in order to measure cross-recurrence of mother and infant vocalizations, cross-recurrence coordination variables between one shuffled mother vocalization dataframe and one shuffled infant vocalization dataframe were calculated (following procedure described in the methods section above). This was then repeated 499 times with the rest of the shuffled dataframes.
5. The 500 calculated variables from shuffled data frames were then averaged together to create one randomized baseline calculation representing the value of coordination by chance occurrence.

BIBLIOGRAPHY

Akhtar, N., Dunham, F., & Dunham, P. J. (1991). Directive interactions and early vocabulary development: The role of joint attentional focus. *Journal of child language, 18*(01), 41-49.

American Psychiatric Association. (2013). *The Diagnostic and Statistical Manual of Mental Disorders (5th Ed.)*. Arlington, VA: American Psychiatric Publishing.

Bakeman, R., & Adamson, L. B. (1986). Infants' conventionalized acts: Gestures and words with mothers and peers. *Infant Behavior and Development, 9*(2), 215-230.

Baldwin, D. A. (1991). Infants' Contribution to the Achievement of Joint Reference. *Child Development, 62*(5), 875-890.

Bedford, R., Elsabbagh, M., Gliga, T., Pickles, A., Senju, A., Charman, T., & Johnson, M. H. (2012). Precursors to social and communication difficulties in infants at-risk for autism: gaze following and attentional engagement. *Journal of Autism and Developmental Disorders, 42*, 2208+.

Beebe, B., Alson, D., Jaffe, J., Feldstein, S., & Crown, C. (1988). Vocal congruence in mother-infant play. *Journal of Psycholinguistic Research, 17*(3), 245-259.

Bigelow, A. E. (1998). Infants' sensitivity to familiar imperfect contigencies in social interaction. *Infant Behavior and Development, 21*(1), 149-162.

Bigelow, A. E., MacLean, K., Proctor, J., Myatt, T., Gillis, R., & Power, M. (2010). Maternal sensitivity throughout infancy: Continuity and relation to attachment security. *Infant Behavior and Development, 33*(1), 50-60.

Bloom, K., Russell, A., & Wassenberg, K. (1987). Turn taking affects the quality of infant vocalizations. *Journal of child language, 14*(2), 211-227.

Brooks, R., & Meltzoff, A. N. (2005). The development of gaze following and its relation to language. *Developmental Science, 8*(6), 535-543.

Brugman, H., & Russel, A. (2004). *Annotating Multi-media/Multi-modal Resources with ELAN.* Paper presented at the LREC.

Campbell, S. B., Leezenbaum, N. B., Mahoney, A. S., Day, T. N., & Schmidt, E. N. (2015). Social engagement with parents in 11-month-old siblings at high and low genetic risk for autism spectrum disorder. *Autism, 19*(8), 915-924.

Carpenter, M., Nagell, K., Tomasello, M., Butterworth, G., & Moore, C. (1998). Social Cognition, Joint Attention, and Communicative Competence from 9 to 15 Months of Age. *Monographs of the Society for Research in Child Development, 63*(4), i-174.

Colombo, J. (2001). The Development of Visual Attention in Infancy. *Annual Review of Psychology, 52*(1), 337-367.

Corkum, V., & Moore, C. (1998). The origins of joint visual attention in infants. *Developmental Psychology, 34*(1), 28-38.

Crown, C. L. (1991). Coordinated Interpersonal Timing of Vision and Voice as a Function of interpersonal Attraction. *Journal of Language and Social Psychology, 10*(1), 29-46.

Farroni, T., Massaccesi, S., Pividori, D., & Johnson, M. H. (2004). Gaze following in newborns. *Infancy, 5*(1), 39-60.

Feldman, R. (2007). Parent–infant synchrony and the construction of shared timing; physiological precursors, developmental outcomes, and risk conditions. *Journal of Child Psychology and Psychiatry, 48*(3-4), 329-354.

Fenson, L., Dale, P., Reznick, S. J., Thal, D. J., Bates, E., Hartung, J. P., . . . Reilly, J. S. (1993). *The MacArthur Communicative Development Inventories: User's guide and technical manual*. Baltimore: Paul H. Brookes Publishing Company.

Field, T. M. (1981). Infant gaze aversion and heart rate during face-to-face interactions. *Infant Behavior and Development, 4*, 307-315.

Fogel, A. (1977). Temporal organization in mother-infant face-to-face interaction. *Studies in mother-infant interaction*, 119-152.

Friedman, S., Thompson, M. A., Crawley, S., Criticos, A., Drake, D., Iacobbo, M., . . . Richardson, L. (1976). Mutual Visual Regard during Mother-Infant Play. *Perceptual and Motor Skills, 42*(2), 427-431.

Goldstein, M. H., King, A. P., & West, M. J. (2003). Social interaction shapes babbling: Testing parallels between birdsong and speech. *Proceedings of the National Academy of Sciences, 100*(13), 8030-8035.

Goldstein, M. H., Schwade, J., Briesch, J., & Syal, S. (2010). Learning While Babbling: Prelinguistic Object-Directed Vocalizations Indicate a Readiness to Learn. *Infancy, 15*(4), 362-391.

Goldstein, M. H., & Schwade, J. A. (2008). Social feedback to infants' babbling facilitates rapid phonological learning. *Psychol Sci, 19*(5), 515-523.

Goldstein, M. H., Schwade, J. A., & Bornstein, M. H. (2009). The Value of Vocalizing: Five-Month-Old Infants Associate Their Own Noncry Vocalizations With Responses From Caregivers. *Child Development, 80*(3), 636-644.

Gros-Louis, J., West, M. J., Goldstein, M. H., & King, A. P. (2006). Mothers provide differential feedback to infants' prelinguistic sounds. *International Journal of Behavioral Development, 30*(6), 509-516.

Gros-Louis, J., West, M. J., & King, A. P. (2014). Maternal Responsiveness and the Development of Directed Vocalizing in Social Interactions. *Infancy, 19*(4), 385-408.

Harel, H., Gordon, I., Geva, R., & Feldman, R. (2011). Gaze Behaviors of Preterm and Full-Term Infants in Nonsocial and Social Contexts of Increasing Dynamics: Visual Recognition, Attention Regulation, and Gaze Synchrony. *Infancy, 16*(1), 69-90.

Hsu, H.-C., Fogel, A., & Messinger, D. S. (2001). Infant non-distress vocalization during mother-infant face-to-face interaction: Factors associated with quantitative and qualitative differences☆7. *Infant Behavior and Development, 24*(1), 107-128.

Hudry, K., Chandler, S., Bedford, R., Pasco, G., Gliga, T., Elsabbagh, M., . . . Charman, T. (2014). Early Language Profiles in Infants at High-Risk for Autism Spectrum Disorders. *Journal of Autism and Developmental Disorders, 44*(1), 154-167.

Huttenlocher, J., Haight, W., Bryk, A., Seltzer, M., & Lyons, T. (1991). Early vocabulary growth: Relation to language input and gender. *Developmental Psychology, 27*(2), 236-248.

Ibanez, L. V., Messinger, D. S., Newell, L., Lambert, B., & Sheskin, M. (2008). Visual disengagement in the infant siblings of children with an autism spectrum disorder (ASD). *Autism, 12*(5), 473-485.

Iverson, J. M., Northrup, J. B., Leezenbaum, N. B., Parladé, M. V., Koterba, E. A., & West, K. L. (2017). Early Gesture and Vocabulary Development in Infant Siblings of Children with Autism

Spectrum Disorder. *Journal of Autism and Developmental Disorders, In Press*.

Jaffe, J., Beebe, B., Feldstein, S., Crown, C. L., Jasnow, M. D., Rochat, P., & Stern, D. N. (2001). Rhythms of Dialogue in Infancy: Coordinated Timing in Development. *Monographs of the Society for Research in Child Development, 66*(2), i-149.

Jaffe, J., & Feldstein, S. (1970). *Rhythms of dialogue*. New York and London: Academic Press.

Jasnow, M., & Feldstein, S. (1986). Adult-Like Temporal Characteristics of Mother-Infant Vocal Interactions. *Child Development, 57*(3), 754-761.

Jones, E. J. H., Gliga, T., Bedford, R., Charman, T., & Johnson, M. H. (2014). Developmental pathways to autism: A review of prospective studies of infants at risk. *Neuroscience & Biobehavioral Reviews, 39*(0), 1-33.

Kasari, C., Sigman, M., Mundy, P., & Yirmiya, N. (1988). Caregiver interactions with autistic children. *Journal of abnormal child psychology, 16*(1), 45-56.

Kaye, K., & Fogel, A. (1980). The temporal structure of face-to-face communication between mothers and infants. *Developmental Psychology, 16*(5), 454.

Landry, S. H., Smith, K. E., Miller-Loncar, C. L., & Swank, P. R. (1997). Predicting cognitive-language and social growth curves from early maternal behaviors in children at varying degrees of biological risk. *Developmental Psychology, 33*(6), 1040.

Leezenbaum, N. B., Campbell, S. B., Butler, D., & Iverson, J. M. (2014). Maternal verbal responses to communication of infants at low and heightened risk of autism. *Autism, 18*(6), 694-703.

Masur, E. F. (1982). Mothers' responses to infants' object-related gestures: Influences on lexical development. *Journal of child language, 9*(01), 23-30.

Mendive, S., Bornstein, M. H., & Sebastián, C. (2013). The role of maternal attention-directing strategies in 9-month-old infants attaining joint engagement. *Infant Behavior and Development, 36*(1), 115-123.

Messinger, D., Young, G. S., Ozonoff, S., Dobkins, K., Carter, A., Zwaigenbaum, L., . . . Constantino, J. N. (2013). Beyond Autism: A Baby Siblings Research Consortium Study of High-Risk Children at Three Years of Age. *Journal of the American Academy of Child and Adolescent Psychiatry, 52*(3), 300-308. e301.

Millar, W. S., & Watson, J. S. (1979). The effect of delayed feedback on infant learning reexamined. *Child Development*, *50*, 747-751.

Moore, C., & Dunham, P. (2014). *Joint attention: Its origins and role in development*: Psychology Press.

Morales, M., Mundy, P., Delgado, C. E. F., Yale, M., Messinger, D., Neal, R., & Schwartz, H. K. (2000). Responding to Joint Attention Across the 6- Through 24-Month Age Period and Early Language Acquisition. *Journal of Applied Developmental Psychology, 21*(3), 283-298.

Morales, M., Mundy, P., Delgado, C. E. F., Yale, M., Neal, R., & Schwartz, H. K. (2000). Gaze following, temperament, and language development in 6-month-olds: A replication and extension. *Infant Behavior and Development, 23*(2), 231-236.

Mullen, E. M. (1995). *Mullen scales of early learning*: Pearson San Antonio, TX.

Mundy, P., Block, J., Delgado, C., Pomares, Y., Vaughan Van Hecke, A., & Parlade, M. V. (2007). Individual Differences and the Development of Joint Attention in Infancy. *Child Development, 78*(3), 938-954.

Mundy, P., Sigman, M., & Kasari, C. (1994). Joint attention, developmental level, and symptom presentation in autism. *Development and Psychopathology*, *6*(03), 389-401.

Northrup, J. B., & Iverson, J. M. (2015). Vocal Coordination During Early Parent–Infant Interactions Predicts Language Outcome in Infant Siblings of Children with Autism Spectrum Disorder. *Infancy, 20*(5), 523-547.

Northrup, J. B., Libertus, K., & Iverson, J. M. (2017). Response to changing contingencies in infants at high and low risk for autism spectrum disorder. *Autism Research*.

Oller, D. K. (2000). *The emergence of the speech capacity*: Lawrence Erlbaum.

Ozonoff, S., Young, G. S., Belding, A., Hill, M., Hill, A., Hutman, T., . . . Schwichtenberg, A. (2014). The broader autism phenotype in infancy: when does it emerge? *Journal of the American Academy of Child & Adolescent Psychiatry*, *53*(4), 398-407. e392.

Ozonoff, S., Young, G. S., Carter, A., Messinger, D., Yirmiya, N., Zwaigenbaum, L., . . . Dobkins, K. (2011). Recurrence risk for autism spectrum disorders: a Baby Siblings Research Consortium study. *Pediatrics, 128*(3), e488-e495.

Parladé, M., & Iverson, J. (2015). The Development of Coordinated Communication in Infants at Heightened Risk for Autism Spectrum Disorder. *Journal of Autism and Developmental Disorders*, 1-17.

Paul, R., Fuerst, Y., Ramsay, G., Chawarska, K., & Klin, A. (2011). Out of the mouths of babes: vocal production in infant siblings of children with ASD. *Journal of Child Psychology and Psychiatry, 52*(5), 588-598.

Presmanes, A. G., Walden, T. A., Stone, W. L., & Yoder, P. J. (2007). Effects of Different Attentional Cues on Responding to Joint Attention in Younger Siblings of Children with

Autism Spectrum Disorders. *Journal of Autism & Developmental Disorders, 37*(1), 133-144.

Raudenbush, S. W. (2004). *HLM 6: Hierarchical linear and nonlinear modeling*: Scientific Software International.

Raudenbush, S. W., & Bryk, A. S. (2002). *Hierarchical linear models: Applications and data analysis methods* (Vol. 1): Sage.

Robins, D. L., Casagrande, K., Barton, M., Chen, C.-M. A., Dumont-Mathieu, T., & Fein, D. (2014). Validation of the Modified Checklist for Autism in Toddlers, Revised With Follow-up (M-CHAT-R/F). *Pediatrics, 133*(1), 37-45.

Rozga, A., Hutman, T., Young, G. S., Rogers, S. J., Ozonoff, S., Dapretto, M., & Sigman, M. (2011). Behavioral profiles of affected and unaffected siblings of children with autism: contribution of measures of mother-infant interaction and nonverbal communication. *Journal of Autism and Developmental Disorders, 41*, 287+.

Sameroff, A. E. (2009). *The transactional model of development: How children and contexts shape each other*: American Psychological Association.

Senju, A., & Csibra, G. (2008). Gaze Following in Human Infants Depends on Communicative Signals. *Current Biology, 18*(9), 668-671.

Tamis-LeMonda, C. S., Bornstein, M. H., & Baumwell, L. (2001). Maternal Responsiveness and Children's Achievement of Language Milestones. *Child Development, 72*(3), 748.

Tarabulsy, G. M., Tessier, R., & Kappas, A. (1996). Contingency detection and the contingent organization of behavior in interactions: Implications for socioemotional development in infancy. *Psychological Bulletin, 120*(1), 25.

Tomasello, M., & Farrar, M. J. (1986). Joint Attention and Early Language. *Child Development, 57*(6), 1454-1463.

Topping, K., Dekhinet, R., & Zeedyk, S. (2012). Parent–infant interaction and children's language development. *Educational Psychology, 33*(4), 391-426.

Trevarthen, C., & Aitken, K. J. (2001). Infant Intersubjectivity: Research, Theory, and Clinical Applications. *The Journal of Child Psychology and Psychiatry and Allied Disciplines, 42*(1), 3-48.

Tronick, E., Als, H., & Brazelton, T. B. (1980). Monadic phases: A structural descriptive analysis of infant-mother face to face interaction. *Merrill-Palmer Quarterly of Behavior and Development*, 3-24.

Van Egeren, L. A., Barratt, M. S., & Roach, M. A. (2001). Mother–infant responsiveness: Timing, mutual regulation, and interactional context. *Developmental Psychology, 37*(5), 684-697.

Wan, M. W., Green, J., Elsabbagh, M., Johnson, M., Charman, T., & Plummer, F. (2013). Quality of interaction between at-risk infants and caregiver at 12-15 months is associated with 3-year autism outcome. *Journal of Child Psychology & Psychiatry, 54*(7), 763-771.

Warlaumont, A. S., Oller, D. K., Dale, R., Richards, J. A., Gilkerson, J., & Xu, D. (2010). *Vocal interaction dynamics of children with and without autism.* Paper presented at the 32nd Annual Conference of the Cognitive Science Society Austin, TX.

Willett, J. B., Singer, J. D., & Martin, N. C. (1998). The design and analysis of longitudinal studies of development and psychopathology in context: Statistical models and methodological recommendations. *Development and Psychopathology, 10*(02), 395-426.

Winder, B. M., Wozniak, R. H., Parladé, M. V., & Iverson, J. M. (2013). Spontaneous initiation of communication in infants at low and heightened risk for autism spectrum disorders. *Developmental Psychology, 49*(10), 1931-1942.

Wu, Z., & Gros-Louis, J. (2014). Infants' prelinguistic communicative acts and maternal responses: Relations to linguistic development. *First Language, 34*(1), 72-90.

Yale, M. E., Messinger, D. S., Cobo-Lewis, A. B., & Delgado, C. F. (2003). The temporal coordination of early infant communication. *Developmental Psychology, 39*(5), 815-824.

Yirmiya, N., Gamliel, I., Pilowsky, T., Feldman, R., Baron-Cohen, S., & Sigman, M. (2006). The development of siblings of children with autism at 4 and 14 months: Social engagement, communication, and cognition. *Journal of Child Psychology and Psychiatry, 47*(5), 511-523.

Young, G. S., Merin, N., Rogers, S. J., & Ozonoff, S. (2009). Gaze behavior and affect at 6 months: predicting clinical outcomes and language development in typically developing infants and infants at risk for autism. *Developmental Science, 12*(5), 798-814.

Yu, C., & Smith, L. B. (2013). Joint Attention without Gaze Following: Human Infants and Their Parents Coordinate Visual Attention to Objects through Eye-Hand Coordination. *PloS one, 8*(11), e79659.