Walking, Exploration, and Communication: An Investigation of Developmental Cascades in Infants with Low vs. Heightened Risk for Autism Spectrum Disorder

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Learning to walk enables infants to travel faster and farther, exploring more of their environment (e.g., Adolph & Tamis-LeMonda, 2012). This enhanced mobility may have a cascading effect on infants' exploration and social interactions. Notably, infants with autism spectrum disorder (ASD) begin walking later and with reduced proficiency compared with neurotypical infants (e.g., Esposito, Venuti, Apicella, & Muratori, 2011; Minshew, Sung, Jones, & Furman, 2004; West, 2018; Bhat et al., 2011). This may lead infants with ASD to experience this transition differently. This dissertation had two overarching objectives: 1.) investigate whether the onset of walking corresponds to a shift in infants' interactions with objects and people, and 2.) examine whether and how this cascade diverges in ASD. To this end, we measured longitudinal changes in infants' locomotion, object interactions, communication, and caregivers' contingent responses during the transition to walking in two cohorts of infants. The first cohort consisted of 25 infants with no family history of ASD (Low Risk; LR). The second consisted of were 91 infants who are at Heightened Risk (HR) for ASD by virtue of having an older sibling with an ASD diagnosis. In particular, we compared data across three HR outcome groups: infants who later developed ASD (HR-ASD), infants with language delay (HR-LD), and infants with no diagnosis (HR-ND). Across this transition, neurotypical infants walked more, played with a greater variety of objects, produced more frequent gestures and vocalizations, coordinated communicative behaviors with locomotion more frequently, and received proportionately more contingent verbal responses from caregivers. These findings lend support to the notion that learning to walk instigates a cascade, affecting many other domains of development. This transition differed for HR-ASD infants in important ways. Compared to their neurotypical peers, HR-ASD infants showed reduced growth in the variety of objects they played with, the frequency of gestures and vocalizations they produced, reduced coordination of communication and locomotion, and fewer verbal responses from caregivers. This dissertation thus provides evidence that the transition to walking marks a point in development when the gap in communication and social-interaction between ASD and neurotypical infants widens.

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Preface

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1.0 INTRODUCTION

Learning to walk changes how infants interact with the environment. They travel faster and farther than before, accessing far-off objects and people on the way (Adolph & Tamis-LeMonda, 2012). In addition, walk onset coincides with accelerated growth in vocabulary, regardless of infant age (He, Walle & Campos, 2015; Walle, 2016; Walle & Campos, 2014; West, Leezenbaum, Northrup & Iverson, 2017). When infants begin walking, the number of words that they say and understand increases substantially. What might account for this association? Although it is likely driven by multiple factors, one possibility is that walking has cascading effects on infants' interactions with objects and people that in turn support language learning. For example, an infant may forage for an alluring object, and then walk to another room to share it with a caregiver. These "moving" social bids elicit timely responses from caregivers (e.g., "What did you find? Is that your bear?"; Karasik, Tamis-LeMonda & Adolph 2014), which may benefit word learning. The cascade hypothesis asserts that it is not walking per se, but rather the *opportunities that walking creates* for exploration and social communication that ultimately assist language development.

If walking offers enhanced opportunity for exploration and social interaction, then walking delays or difficulties could constrain these opportunities. We hypothesize that this is the case for infants with autism spectrum disorder (ASD). Mounting evidence indicates that motor function is atypical in ASD, including walking (e.g., Bhat, Landa & Galloway, 2011; Fournier, Hass, Naik, Lodha, & Cauraugh, 2010; West, 2018). Indeed, walking emerges later and with less proficiency for infants with ASD compared to neurotypical[1] infants (Esposito, Venuti, Apicella, & Muratori, 2011; Minshew, Sung, Jones, & Furman, 2004; West, 2018; Bhat et al., 2011). This disruption could alter the exploratory and communicative behaviors of infants with ASD, and consequently the language infants elicit from caregivers.

This dissertation has two overarching objectives. The first is to investigate the cascade hypothesis—that is, that learning to walk corresponds to a shift in infants' interactions with objects and people. The second is to examine whether and how this cascade diverges in ASD. These objectives are motivated by the notion that development (both typical and atypical) is best understood by considering change in multiple domains simultaneously. “Motor”, “communication”, and “exploration” behaviors are not produced separately—they are integrated together within more complex behavioral sequences. A major setting event in one domain can reverberate across other, seemingly unrelated domains (e.g., Thelen & Smith, 1998; Campos et al., 2000). Here, we examine whether the emergence of walking is such an event. In the following sections, I review current literature on walking-related changes in infant and caregiver behaviors. This is followed by an overview of research on infant walking and communicative development in ASD.

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[1] “Neurotypical” (an abbreviation of “neurologically typical”) refers to individuals *without* ASD or another neurological condition. This term reflects a neurodiversity perspective, which advocates that ASD is part of natural variation in humans, and should be recognized as a social category. The absence of a term for non-autistic individuals implies a “normal” default. For this reason, we use the term neurotypical to refer to individuals not on the autism spectrum.

Before proceeding, however, three caveats are in order. First, we hypothesize that walking is *participatory* in the development of infants' social and exploratory behaviors—not that it is necessary or sufficient. Clearly walking is unnecessary for advances in exploration and communication to occur. Infants begin to vocalize, gesture, and explore objects well before they begin walking. Further, although motor and communication deficits do frequently co-occur (e.g., Trauner, Wulfeck, Tallal & Hesselink, 2000; Paquet et al., 2015), some infants with significant motor impairments display typical communicative development. For instance, infants with type 2 spinal muscular atrophy experience severe deprivation in locomotor experiences (most are never able to walk unaided), but nevertheless they communicate typically (Riviere, Lecuyer & Hickmann, 2009). We propose that for typically developing infants, all else being equal, walking acts as an agent of developmental change. This does not preclude other, alternative developmental pathways.

Second, there are many complex and multifaceted ways by which walking and communication could interrelate across development. The scope of the present study is therefore necessarily limited. Our focus is measuring how infants' social communication and caregivers' responses to this communication changes as infants transition from crawling to walking. Of course, walking is probably multiply determined by infants' social communicative context. Caregivers' behaviors encourage and constrain locomotion. They call their infants to them, direct them to retrieve far-off objects, and place them in high chairs and car seats that prevent movement. Relatedly, advances in infant communication could provide motivation to walk. For example, the desire to engage socially may drive infants to locomote and seek out caregivers. And in fact, infants who display a stronger motivation to move at 7 months (as measured by infants' activity level, persistence, and the strength of stimuli required to elicit motor actions) walk earlier than less motivated infants (Atun-Einy, Berger & Scher, 2013). The interconnections among walking, exploration, and social-communication behaviors are numerous and elaborate, and this research cannot provide a full account of these mechanisms. Rather, our objective is to probe whether a developmental cascade hypothesis is supported by measuring longitudinal changes in exploration and communication during this transition.

Finally, given the phenotypic complexity of ASD (e.g., Wozniak, Leezenbaum, Northrup, West & Iverson, 2016), it is clear that delayed or disrupted walking cannot fully account for atypical communication among young children with ASD. Infants with ASD are vulnerable to communication deficits even prior to walk onset (e.g., Iverson et al., 2017). Nonetheless, disrupted walking may compound upon this vulnerability, widening the gap between ASD and neurotypical infants.

1.1 The Transition to Walking in Neurotypical Development

Infants typically transition from crawling to walking in the second year of life (e.g., Adolph & Berger, 2006). The incentives to do so are clear. Walking enables infants to travel great distances—up to 700 meters per hour. Even newly walking infants locomote three times farther than expert crawlers (Adolph & Tamis-LeMonda, 2014). In addition, walkers gain an elevated vantage point by standing upright. Whereas crawlers' view is dominated by the floor in front of them, walkers have a broad view of the landscape (Kretch, Franchak & Adolph, 2014). These distinct vantage points may guide infants' exploration in different ways. Walkers travel to distant objects and people more frequently, whereas crawlers tend to interact within arms' reach (Karasik, Adolph, Tamis-LeMonda & Zuckerman, 2012). An added benefit is that walking frees the hands during locomotion, allowing walkers to carry objects with them (Karasik, Adolph, Tamis-LeMonda & Zuckerman, 2012).

Learning to walk may prompt changes in infants' social interactions. Infants initiate social interactions more often after they walk (e.g., by gesturing or vocalizing; Clearfield et al., 2008; Clearfield, 2011; Walle, 2016). The format of social interactions may also change. Researchers have observed a back-and-forth pattern of social interaction among walking infants, where walkers repeatedly travel between a parent and a distal location (Walle & Campos, 2014). Notably, walkers display more "moving" social bids (e.g., they carry objects over to caregivers to bid for their attention) than do same-aged crawlers (Karasik, Tamis-LeMonda & Adolph, 2011). In turn, caregivers are more likely to respond to these moving bids than to stationary bids, presumably because stationary bids can be easily overlooked (Karasik, Tamis-LeMonda & Adolph, 2014). This distinction could be impactful over the course of day-to-day routines, when parents' attention is divided between infant care and other everyday activities. Walkers' ability to approach their caregiver with ease may foster more frequent social interactions.

There are multiple reasons why this shift may benefit infants' language development. Bouts of joint engagement—in which dyads attend to one another or an object, and a caregiver provides verbal input—facilitate word learning (e.g., Tamis-LeMonda, Kuchirko & Song, 2014; Tomasello & Farrar, 1986; Yu & Smith, 2012). If the frequency or quality of these interactions increases with walking, it may prompt a simultaneous boost in language growth. Additionally, infants' object interactions may affect the language they hear and consequently learn. Caregivers frequently "follow in" and talk about the objects with which infants are currently interacting (e.g., Bornstein, Tamis-LeMonda, Hahn & Haynes, 2008; West & Iverson, 2017). In particular, they frequently provide the objects' corresponding label (e.g., "Are you talking on the <u>phone</u>?"

West & Iverson, 2017). If walkers access a wider range of objects than crawlers, this diversity may be reflected in the language they elicit (e.g., an infant who plays with six objects may hear descriptions of these six objects from a caregiver).

Evidence suggests that the onset of walking coincides with increased growth in language acquisition (He, Walle & Campos, 2015; Oudgenoeg-Paz, Volman & Leseman, 2012; Walle, 2016; Walle & Campos, 2014; West, Leezenbaum, Northrup & Iverson, 2017). An initial study by Walle and colleagues (2014) measured infant vocabulary longitudinally across the transition to walking. Walking experience predicted vocabulary growth (both receptive and expressive) above and beyond infants' chronological age. Moreover, while age predicted a linear pattern of growth, walking experience predicted a nonlinear trend, with growth accelerating following walk onset. This finding has since been replicated in multiple diverse samples (He, Walle & Campos, 2015; Walle, 2016; Walle & Campos, 2014; West, Leezenbaum, Northrup & Iverson, 2017). Researchers have hypothesized that this phenomenon is driven by accompanying changes in infants' social and object interactions (i.e., the developmental cascade hypothesis). To date, however, this hypothesis has been largely untested.

Past research on the association between walking and communication has been predominantly cross-sectional, involving between-subjects comparisons of age-matched crawlers and walkers. However, this design may be confounded by infants' general developmental ability. That is, it cannot tell us whether walking and communication are functionally related, or whether precocious walkers also just happen to be precocious communicators. The few studies that do use longitudinal designs are limited to two time points (e.g., pre-walk and post-walk; Clearfield, 2011). This obscures the functional form of change over this transition (i.e., there is no baseline comparison for the rate of change prior to walking, and no information about the shape of change). The present study addresses these limitations by following infants longitudinally for seven months as they transition from crawling to walking. We investigate whether walk onset is concomitant with shifts in infants' object interactions, communication, and verbal responses from caregivers. In doing so, we provide new knowledge regarding the extent to which walk onset is a setting event in infant development.

1.2 The Transition to Walking in ASD

Autism spectrum disorder (ASD) is a neurodevelopmental disorder characterized by difficulty with social-communication and the presence of restricted or repetitive behaviors (DSM 5; American Psychiatric Association, 2013). Because ASD is not typically diagnosed until 40 months of age (Christensen et al., 2016), it is difficult for researchers to study the development of ASD in infancy. To circumvent this barrier, researchers have focused on the infant siblings of children with ASD, who are at heightened biological risk (Heightened Risk; HR) of developing ASD. The recurrence rate for HR infants is 18.7%, which is well above the prevalence in the general population (e.g., Ozonofff et al., 2011). Prospectively studying HR infants enables researchers to probe early-occurring differences between infants who are later diagnosed with ASD and those who are not.

Although not included in the diagnostic criteria, delays in gross motor development are well-documented in ASD (e.g., Bhat, Landa & Galloway, 2010; Garrido et al., 2017; West, 2018). In particular, evidence suggests the development of walking is affected. One study using retrospective parent report indicated that infants with ASD walked up to 2 months later than neurotypical infants (Ozonoff et al., 2008). This finding was corroborated by analysis of retrospective home videos, which revealed that infants with ASD did not display mature walking until 3 months after their neurotypical peers. Additionally, studies find that gait—the pace and spatial features of footfalls—differs in ASD relative to neurotypical infants (Esposito et al., 2008, 2011). This investigation led researchers to conclude the following:

> Children with a diagnosis of Autistic Disorder have shown (i) problems performing the heel-to-toe pattern, (ii) more asymmetric posture of the arm while walking, (iii) higher frequency of anomalies in general movement, both for the presence of stereotyped movement and "waddling walk". (p. 266).

Taken together, these findings suggest that atypical walking development may be characteristic of the disorder.

Evidence of atypical walking has led researchers to investigate whether the walking-language link described previously is disrupted in ASD. Two studies examined whether parent report of walk onset age (retrospectively collected) predicts language ability, and they have yielded mixed findings. Kim (2008) reported that walk onset age did not predict language in preschool-aged children with ASD. By contrast, Bedford and colleagues (2015) found that walk onset age predicted language growth from 2-9 years—however, this effect became non-significant after controlling for overall gross motor ability (i.e., walking age was not a unique predictor). Importantly, neither of these studies examined language growth *at the time of walk onset*.

To address this gap, my colleagues and I examined longitudinal trajectories of receptive and expressive vocabulary development during the transition to walking in HR and LR infants. We then compared the trajectories for three subgroups of HR infants who varied in developmental outcomes assessed at age 3 to those of a group of infants with no family history of ASD (Low Risk; LR). For LR infants and HR infants with no ASD diagnosis or other developmental concerns (HR-ND), walk onset coincided with additional linear growth in receptive and expressive vocabulary. The same pattern was observed for HR infants with language delay (HR-LD), although growth was attenuated relative to LR infants. Only HR infants later diagnosed with ASD (HR-ASD) did *not* demonstrate increased language growth at walk onset (West, Leezenbaum, Northrup & Iverson, 2017).

What might account for the lack of growth in vocabulary observed among HR-ASD infants during the transition to walking? There are at least two possible, non-mutually exclusive explanations. One has to do with potential differences in walking proficiency after walking onset has been achieved. Not only does walking emerge later in ASD, but as previously described, infant gait is less fluid and less symmetrical (Esposito et al., 2008, 2011). Children with ASD also display qualitative differences in walking compared to neurotypical children, including difficulty with balance, slower speed, and a greater degree of dysrhythmia, a neurological sign of reduced motor control (e.g., Jansiewicz et al., 2006; Hallett et al., 1993). If walking is more effortful, infants with ASD may walk less frequently or for shorter distances, potentially reducing the benefits of enhanced locomotion for communication. Moreover, difficulty walking may lead infants with ASD to crawl and cruise (take steps while their body weight is supported, typically by furniture) for a more extended time than is typical. Longer reliance on crawling and cruising would likely correspond to slower speed, diminished visual vantage point, and fewer opportunities to explore. These less-advanced forms of locomotion may lead infants with ASD to very different experiences. Thus, the present study will examine whether HR-ASD infants display an atypical pattern of walking development compared to their neurotypical peers.

Second, the social function of walking may differ in ASD. The ability to walk offers infants increased autonomy to initiate social interactions, which may lead infants with ASD to different experiences than peers. For instance, affected infants may approach social partners less often, or disengage from social interactions more frequently. Recall that past studies have observed an increase in back-and-forth social interactions following walk onset: neurotypical infants walked to-and-from their caregiver and distal locations, prompting verbal input upon their return (e.g., Mahler, 1975; Biringen, Emde, Campos & Appelbaum, 2008). Even if infants with ASD travel comparable distances as their peers, they may seek out social interactions less often.

This hypothesis is supported by abundant research showing that infants with ASD initiate social interactions less frequently than their peers (see Jones et al., 2014, for a review of social-communicative development in ASD). Further support comes from a study of HR and LR infants that examined object sharing (bringing an object to a caregiver) longitudinally across the transition to walking (Srinivasan & Bhat, 2016). All infants showed the expected increase in object sharing; but the increase was lessened in HR infants. This attenuation may be driven by a subset of HR infants who later developed ASD, but diagnostic outcome data were unavailable in this study. The present study builds on this work by examining how HR-ASD infants' communicative behaviors and object interactions change as they gain walking experience. We will test whether these trajectories differ from those of their neurotypically developing peers.

1.3 The Present Study

The overarching goal of this dissertation is to investigate: 1.) how infants' locomotion, interactions with objects, communication, and the responses they elicit from caregivers change during the transition to walking, and 2.) how these changes differ for infants who develop ASD. Mounting evidence indicates that motor milestones are correlated with advances in far-flung psychological domains (e.g., Clearfield, 2004; Gottwald, Achermann, Marciszko, Lindskog & Gredebäck, 2016; Libertus & Violi, 2016; Schwarzer, Freitag, Buckel, & Lofruthe, 2013). This work has identified only the book-ends of these developmental cascades, leaving open questions about the intermediary links. This study investigates potential intermediary links for one such developmental cascade—the link between walking and communication. To this end, we followed infants for seven repeated observations anchored by their walk onset—four months prior to walk onset, and three months after—enabling us to measure baseline growth prior to walk onset, and identify the functional form of developmental change across multiple domains. The research has four specific aims:

Aim 1: Measure the functional form of change in locomotion across the transition to walking in LR infants, and in three HR outcome groups. This will be the first study to our knowledge to examine whether the longitudinal progression from crawling to walking differs for HR-ASD infants. Based on previous research, we hypothesize that:

1. Following walk onset, LR, HR-ND, and HR-LD infants will show an increase in time spent walking and a corresponding decrease in less-advanced crawling and cruising.
2. HR-ASD infants will display an attenuated increase in time spent walking and will continue to crawl and cruise for longer in development than their peers.

3. LR, HR-ND, and HR-LD infants will increasingly carry objects and locomote to and from social partners as they gain walking experience.
4. HR-ASD infants will approach social partners less frequently than their peers.

Aim 2: Measure the functional form of change in object interactions across the transition to walking in LR infants, and in three HR outcome groups. Although previous research finds that infants access more distal objects after they begin walking, no study has examined whether they access a greater variety of objects overall. We expected that:

1. The variety of objects that LR, HR-ND, and HR-LD infants access will increase following walk onset.
2. Because we expect HR-ASD infants to locomote less frequently than their peers, we anticipated that they will correspondingly encounter fewer objects.

Aim 3: Measure the functional form of change in infant communication across the transition to walking in LR infants, and in three HR outcome groups. Previous research suggests that walk onset corresponds to a shift in infant communication. We have several hypotheses related to how communication changes in quantitative and qualitative ways with the emergence of walking:

1. LR and HR-ND infants will increase production of gestures and vocalizations following walk onset. Further, these behaviors will be increasingly coupled with infants' social gaze and locomotion behavior.
2. Based on past work, we expect that growth in communication will be attenuated for HR-LD infants relative to LR infants (e.g. Iverson et al., 2017; Parlade & Iverson, 2015).

3. For HR-ASD infants, walk onset will *not* be accompanied by increased growth in gesture and vocal production. Because we expect that walking is less proficient in ASD, we anticipate that communication will be paired with locomotion (i.e., "moving") less often than for LR infants.

Aim 4: Measure the functional form of change in caregiver contingent responses across the transition to walking in LR infants, and in three HR outcome groups. Previous research indicates that walking infants produce more moving bids than do crawlers (Karasik, Tamis-LeMonda & Adolph, 2011), and caregivers are more likely to respond to moving bids than stationary bids (Karasik, Tamis-LeMonda & Adolph, 2014). Based on this work, we hypothesize that:

1. Walk onset will correspond to increased growth in caregiver responses to LR, HR-ND, and HR-LD infants. Further, these responses will be more likely to contain translations of infants' communicative acts (i.e., a label that corresponds to the infants' action; for example, if the infant points to a cup and the caregiver says "Do you want your <u>sippy cup</u>?").
2. In light of our hypothesis that "moving" communication will be reduced in HR-ASD infants, we also expect that the responses they elicit from caregivers will be reduced relative to LR infants.

2.0 METHODS

2.1 Participants

This study included data from two cohorts of infants followed as part of two separate longitudinal studies. The first included 25 infants (15 female) with no first-degree relatives with ASD. These infants were at low risk (LR) for developing ASD. Of these infants, 16 had at least one older typically-developing sibling. The remaining 9 infants were first-born[2]. The second consisted of 91 infants (43 female) who had a full biological sibling with an ASD diagnosis (heightened risk; HR). Prior to HR infants' enrollment, the older ASD sibling was administered the Autism Diagnostic Observation Schedule-Generic (ADOS-G; Lord et al., 2000) by a trained, research-reliable clinician. If the older sibling's score met threshold for either Autistic Disorder (AD) or ASD, the HR infant was enrolled.

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[2] To investigate the effect of birth order, we ran growth models with LR infants only, and included Birth Order as a predictor of intercept and slope terms. Birth Order did not significantly differentiate LR infants on any variable other than gesture production; first-born LR infants produced more gestures at the intercept, $p = 0.028$, but slope terms did not differ between groups. In light of this difference, we re-ran the final model of gesture development, including all HR groups and *only* later-born LR infants. The pattern of significant differences between LR and HR outcome groups was unchanged by doing so.

Infants from both samples were from full-term, uncomplicated pregnancies and from monolingual English-speaking households. Demographic characteristics were similar across cohorts. In total, 105 infants (81 HR, 24 LR) were Caucasian, 10 (HR) were Hispanic, and one LR infant was Asian American. Parents across groups were highly educated. The majority of parents held either a college degree or had completed some college. Information about income was unavailable, but Nakao-Treas occupational prestige scores (Nakao & Treas, 1994) were calculated to provide an index of social class. These scores were calculated using fathers' occupations because many of the mothers in both groups stayed at home with their infants. Overall, as is common in ASD research (e.g. Durkin et al., 2008), HR infants had older mothers, $F(1,101) = 4.57$, $p = 0.035$, and fathers, $F(1,101) = 8.61$, $p = 0.004$, compared with LR infants. There were no other significant differences between groups. Table 1 displays demographic information for LR and HR participants in the study.

Table 1 Demographic Information for Low Risk (LR) and Heightened Risk (HR) groups

	LR (n = 25)		HR (n = 91)	
Gender				
Female (%)	10	(40%)	43	(47%)
Male (%)	15	(60%)	48	(53%)
Racial or ethnic minority (%)	1	(4%)	10	(11%)
Mean age for Mothers (sd)	31.92	(4.85)	34.19	(4.01)
Mean age for Fathers (sd)	33.08	(4.00)	36.68	(5.10)
Mean Parent Education[a] (sd)	1.38	(0.50)	1.22	(0.50)
Mean Paternal Occupational Prestige[b] (sd)	48.18	(22.82)	53.08	(18.90)

[a] Parent education based on averaging education scores for mothers and fathers. 0 = High school, 1 = Some college or college degree; 2 = Graduate or professional school
[b] Nakao–Treas occupational prestige score. Unable to calculate for 4 LR and 5 HR fathers.

2.2 Procedure

For both LR and HR groups, infants were videotaped in their homes for approximately 45 minutes of unstructured and semi-structured play at each visit. However, the observation schedule for the two groups differed. LR infants were seen every 2 weeks from 2-19 months and did not have follow-up visits in the toddler years. HR infants were visited monthly from 5-14 months, with follow-up visits at 18, 24, and 36 months. Here we focused on a window of seven visits surrounding infants' walk onset (regardless of chronological age). This window began with the visit occurring 4 months prior to walk onset and ended with the visit occurring 3 months after walk onset. Thus, seven timepoints were included for each infant, and the mid-point was the final crawling-only visit (i.e., the visit just prior to infants' walk onset). Note that although LR infants were seen bimonthly, only whole month visits were included (i.e., if a LR infant began walking at 10.5 months, the 11-month visit was designated as walk onset). This ensured that any risk status differences were not an artifact of different observation schedules.

Walk onset was established through parent report. For both cohorts, parents were given a calendar to track their infants' motor milestones. Walk onset was defined as the first visit when the infant took three consecutive, alternating, and independent steps with no support from furniture or a caregiver. Although walk onset could have occurred between infants' monthly visits, we will refer to the first whole month in which infants met this criterion as "walk onset". If an infant did not attain walk onset by 14 months (the end of the monthly visits), parents were contacted by phone each month thereafter to establish walk onset. This occurred for 14 HR infants (6 ND, 4 LD, 4 ASD). Thus, these infants only contributed partial data to analyses. Because this missing data did not occur at random, we ran additional models with these infants removed. Significant findings were unchanged by excluding these infants, so results reported include data from the full sample.

2.3 Outcome Measures

Three measures were collected in service of determining HR infants' outcome group status. These were collected at 18, 24, and 36-month follow up visits. These measures are detailed below, followed by a description of how scores were used in determining HR infants' outcome group membership.

2.3.1 MacArthur-Bates Communicative Development Inventory

At 18, 24, and 36 months, the MacArthur-Bates Communicative Developmental Inventory (CDI; Fenson et al., 2002) was completed for HR infants by the primary caregiver. Ample work indicate that the CDI is reliable and valid in measuring language ability, and it is sensitive to detect patterns of atypical language development across a variety of samples, including in ASD (e.g., Charman, Drew, Baird, & Baird, 2003; Dale, Bates, Reznick, & 23 Morisset, 1989; Fenson et al., 1994; Luyster, Qiu, Lopez, & Lord, 2007; Miller, Sedey, & Miolo, 1995; Mitchell et al., 2006; Thal, O'Hanlon, Clemmons, & Fralin, 1999).

During infants' 18-month visit, caregivers completed the Words and Gestures form of the CDI (CDI-I), or the Words and Sentences form (CDI-II). The form parents received depended on the infants' language ability. If the child had very few words (as indicated by the caregiver), the caregiver completed the CDI-I. If the infant was producing words frequently or combining words, the caregiver completed the CDI-II. The CDI-I is a 396-item vocabulary checklist, which requires that parents report: a) words that their infant only understands (receptive language), and b) words that their infant both says and understands (expressive language). Additionally, the CDI-I asks parents to report on their infants' production of gestures and actions.

At infants' 24-month visit, all caregivers completed the CDI-II. The CDI-II is a 680-item vocabulary checklist. Caregivers are asked to report on words their infant says. It also includes questions regarding the morphology and syntax of the infants' language.

Finally, at the 36-month visit, parents completed the CDI-III. The CDI-III is a 100-item checklist in which caregivers are asked to report on words their infant says. In addition, it includes 12 questions inquiring about infants' grammatical complexity, and 12 questions inquiring about the semantics and pragmatics of infants' speech. It is appropriate for infants aged 30-37 months.

2.3.2 Mullen Scales of Early Learning

At the 18, 24, and 36-month follow up visits, HR infants were administered the Mullen Scales of Early Learning (MSEL; Mullen, 1995). The MSEL is a standardized and normed assessment which is administered by an experimenter. It provides an index of infants' general cognitive functioning from birth through 68 months and is organized into five subsections: Fine Motor, Visual Reception, Expressive Language, Receptive language, and Gross Motor. It has strong internal consistency, ranging from 0.83 to 0.95.

2.3.3 Autism Diagnostic Observation Schedule

When HR infants were 36 months old, they were administered the Autism Diagnostic Observation Schedule-Generic (ADOS-G; Lord et al., 2000). A research-reliable evaluator administered the ADOS. The evaluator was naïve to all prior collected study data. The ADOS is a play-based assessment designed to measure characteristics of ASD in social, communication, and play behaviors. Infants' production of repetitive behaviors is also observed. ADOS items are scored on a scale from 0 to 3—higher scores denote more severe impairment. A scoring algorithm is used to determine whether a threshold for ASD or Autism is met. The ADOS reliably distinguishes children with ASD from neurotypical children and children with other developmental disorders (Lord et al., 2000).

2.4 Outcome Classification

Using scores obtained from the measures described above, HR infants were classified into one of the following three outcome groups according to the following criteria.

Infants were classified as HR-ASD if their score on the ADOS-G met or exceeded the algorithm threshold for ASD or AD *and* they received a clinical best estimate diagnosis of AD, ASD, or PDD-NOS (Pervasive Developmental Disorder-Not Otherwise Specified) using DSM–IV–TR criteria (diagnostic evaluations occurred prior to the release of the DSM–V in 2013). Fifteen HR infants (5 female) were diagnosed with ASD.

Infants were classified as language delayed (HR-LD) if they *did not* receive an ASD diagnosis *and* either of the following criteria were met:

1. Standardized scores on the CDI–II and or CDI–III at or below the 10th percentile at more than one time point between 18 and 36 months.

2. Standardized scores on the CDI–III at or below the 10th percentile and standardized scores on the receptive and/or expressive subscales of the MSEL equal or greater than 1.5 SDs below the mean at 36 months.

These criteria have been used extensively to identify a pattern of language delay in community samples (Gershkoff-Stowe, Thal, Smith, & Namy, 1997; Heilmann et al., 2005; Robertson & Weismer, 1999; Weismer & Evans, 2002) as well as HR infants (Iverson et al., 2018; Ozonoff et al., 2010; Parlade & Iverson, 2015; West et al., 2017). Twenty-six infants were classified as HR-LD (11 female).

The remaining 50 HR infants were classified as No Diagnosis (HR-ND; 28 female). Outcome measures were not part of the study protocol for LR infants, who graduated from the study at 19-months old. There was no indication that LR infants developed atypically.

2.5 Coding

A 10-minute segment of each visit was coded. This segment was selected by taking the first available 10 minutes when dyads were interacting naturally (i.e., when they were instructed to do what they typically do, with no other instruction) and the infant was *not* constrained by a high-chair. For 663 of the 674 sessions, this segment was completely continuous with no pauses (98.8% of LR sessions, 98.2% of HR sessions). However, for 11 sessions it was impossible to find 10 continuous minutes of naturalistic interaction because the infant was intermittently placed in a high chair (1.2% of LR sessions, 1.8% of HR sessions). In these instances, the 10 minutes was broken into two pieces (e.g., from 1:00-6:00 & 10:00-15:00 minutes). A full 10-minutes was scored for every complete session (i.e., no infant had a shorter segment).

Coding was completed by one primary and seven secondary coders, who were naïve to infants' risk status and outcome classification. Coding was completed in version 4.8 of Elan for Windows (http://tla.mpi.nl/tools/tla-tools/elan; Lausberg & Sloetjes, 2009). Each secondary coder was assigned to one of four coding teams, which focused on either locomotion, object interactions, gesture, or vocalizations. Gesture and vocalization coding teams also identified caregiver responses. For each team, secondary coders were trained by double-coding clips with the primary coder until they met threshold scores on all variables for 3 consecutive clips (Cohen's kappa ≥ 0.80 for categorical variables; mean percent agreement ≥ 90% for identification of behaviors; inter-coder correlations ≥ 0.90 for agreement on the duration variables). Following this training period, coders continued to double-code 19% of all clips to ensure data quality and prevent coder drift. Coding discrepancies were discussed and resolved through group consensus. Original codes were used to calculate reliability data. However, the revised codes were used for data included in final analyses. Coding manuals are presented in Appendix B.

2.5.1 Infant Locomotion

All bouts of locomotion were identified at each timepoint. A bout of locomotion was defined as 2 or more steps or crawl-cycles, which occurred within 0.5 second intervals (i.e., if an infant paused for more than 0.5 seconds while locomoting, two separate bouts were coded; e.g., Adolph et al., 2012). A 0.5-second pause marks a meaningful disruption in continuous infant locomotion (e.g., Bril & Breniere, 1989; Garciaguirre, Adolph & Shrout, 2007). The onset of each bout was determined as the first frame in which the infants' leg (or arm in instances of arm-dominant crawl styles) was in motion. The offset was determined when the final step (or crawl cycle) was completed. Bouts were identified as crawling if the infant was on all fours. Bouts were identified as cruising (supported walking) if the infant was upright and was holding onto a source of support (typically furniture). Bouts were identified as walking independently if the infant was upright and was not receiving any external support.

Additionally, coders identified bouts in which the infant approached a social partner. These were coded when the infant was beyond arm's reach of the social partner at the onset of locomotion, and within arm's reach at the offset (note that the infant did not have to take a direct path). Coders also identified bouts in which the infant disengaged from a social partner. These were coded when the infant was within arm's reach at the onset of locomotion, and beyond arm's reach at the offset.

2.5.2 Infant Object Interactions

Next, infants' interactions with objects were coded. For each bout of locomotion, coders identified whether the infant approached an object. Object approaches were identified if the infant was distal to the object at the onset of locomotion, and then touched the object within 2 seconds of the offset of locomotion. For each bout of locomotion, we identified whether the infant carried an object. This was defined as any time the infant held an object and moved it with them as they locomoted. Next, we identified each unique object the infant interacted with (object variety). To count as an interaction, the infants must have touched the object with a hand or finger for at least 0.5 seconds. This prevented incidental "grazes" from being included. When infants interacted with sets of objects (e.g., puzzle pieces, crayons, blocks), the entire set counted as a single object. To illustrate, if an infant touched six different crayons, the event was coded as only one object.

2.5.3 Infant Communication

All deictic gestures produced by infants were coded. We focused only on deictic gestures because they occur frequently in infancy and are not produced as part of ritualized routines (such as waving bye-bye; e.g., Bates et al., 1975). Deictic gestures included: a) gives: infant handed an object to a social partner; b) shows: infant held up an object to show a social partner; c) reaches: infant reached with an open hand to request a distal object; d) index finger points: infant pointed to a distal object with an isolated index finger (i.e., the finger does not contact the object); e.) index finger touches: infant touched an object with an isolated index finger. Only gestures that were produced spontaneously were coded (i.e., gestures that were verbally elicited by a caregiver were excluded; Iverson & Goldin-Meadow, 2005). To illustrate, if a caregiver said, "Where's teddy?" and then baby pointed to teddy, the pointing gesture was not considered spontaneous and was not coded.

Coders also identified all infant vocalizations, defined as any pre-speech sound the infant produced. Vegetative sounds (e.g., coughs, sneezes, breathing) and affective sounds (e.g., laughing, fussing, crying) were not coded.

Next, coders indicated whether previously-identified gestures and vocalizations were directed. The behavior was coded as directed if it was paired with simultaneous eye gaze toward a social partner following the procedure used by Clearfield (2011). Finally, coders identified whether gestures and vocalizations were moving. Behaviors were identified as moving if they temporally overlapped with locomotion, or occurred within 2 seconds of locomotion offset. All gestures and vocalizations not identified as moving were coded as stationary.

2.5.4 Caregiver Responses

Coders indicated whether each previously-identified gesture and vocalization received a contingent verbal response from a caregiver. A verbal response was identified if the caregiver produced a linguistic vocalization (i.e., containing words) within 2 seconds of the infant's gesture or vocalization. These criteria have been previously used to capture patterns of caregivers' contingent responses (e.g., Gros-Louis, West & Goldstein, 2006; Tamis-LeMonda, Bornstein & Baumwell, 2001). For each verbal response identified, coders indicated whether the response contained a translation. A translation was defined as a label corresponding to the infants' focus of attention (e.g., an infant holds up a ball and the caregiver says, "Are your going to throw me your *ball*?"; an infant vocalizes while looking at a car and caregiver says, "That's your favorite *car*"). Consistent with prior work, we took an inclusive approach to identifying translations and included any concrete noun that described all or part of the referent (Leezenbaum, Campbell, Butler & Iverson, 2014; Goldin-Meadow, Goodrich, Sauer & Iverson, 2007). For example, if an infant points to a dog and the caregiver says, "He has big *paws*," "paws" was still counted as a translation even though it does not refer to the entire object.

2.5.5 Inter-rater Reliability

For locomotion variables, mean percent agreement was 92% (71 - 100%) for identification of locomotion bouts and inter-coder correlations were 0.92 (0.77 - 1.00) for the duration of locomotion bouts. Cohen's kappas were κ = 0.97 (0.63 - 1.00) for categorizing locomotion as either crawling, cruising, or walking, κ = 0.93 (0.52 - 1.00) for categorizing locomotion as a social approach, and κ = 0.91 (0.57 - 1.00) for categorizing locomotion as a social disengagement.

For object interaction variables, Cohen's kappas were κ = 0.88 (0.64 - 1.00) for categorizing bouts as object approaches and κ = 0.97 (0.64 - 1.00) for carrying objects. Mean percent agreement for identification of unique objects was 94% (80 - 100%).

For communication variables, mean percent agreement was 83% (64 - 100%) for identification of gestures and 90% (71 - 100%) for identification of vocalizations. Cohen's kappas were κ = 0.92 (0.69 - 1.00) for categorizing the directedness of gestures and κ = 0.97 (0.72 - 1.00), and κ = 0.82 (0.61 - 1.00) for categorizing the directedness of vocalizations. Cohen's kappas were κ =0.97 (0.72 - 1.00) for categorizing gestures as moving and κ = 0.99 (0.80 - 1.00) for categorizing vocalizations as moving.

For caregiver response variables, Cohen's kappas were κ = 0.90 (0.63 - 1.00) for caregiver verbal responses to gestures, κ = 0.89 (0.64 - 1.00) for caregiver verbal responses to vocalizations, κ = 0.95 (0.58 - 1.00) for caregiver translations to gestures, and κ = 0.95 (0.60 - 1.00) for caregiver translations to vocalizations.

2.6 Data Reduction

Raw data coded at each time point in Elan were extracted and exported into Version 24 of IBM SPSS, where individual infants' data were reduced to form the final variables. Each coding session lasted for precisely 10 minutes. Because session duration was standardized and there were no deviations, it was not necessary to account for differences in duration.

For infant locomotion, six primary variables were calculated from the data for each session: a) the total duration of time spent crawling in seconds; b) the total duration of time spent cruising in seconds; c) the total duration of time spent walking independently in seconds; d) the total number of locomotion bouts in which infants approached a social partner; and e) the total number of locomotion bouts in which infants disengaged from a social partner.

Three primary variables were computed separately for each session from the data on infant object interactions: a) the total number of locomotion bouts in which infants approached an object; b) the total number of locomotion bouts in which infants carried an object; and c) the total number of unique objects that the infant interacted with during the session.

For infant communication, four primary variables were calculated: a) the total number of gestures that infants produced during the session; b) the total number of vocalizations that infants produced during the session; c) the total frequency of directed communication; i.e., [directed gestures + directed vocalizations]; and d) the total frequency of moving communication; i.e., [moving gestures + moving vocalizations].

Finally, four primary variables were calculated from the data on caregiver responses: a) the proportion of infants' total communication that received a verbal response, i.e., [(total # caregiver responses to gestures + total # caregiver responses to vocalizations) / (total # infant gestures + total # infant vocalizations)]; b) the proportion of infants' total communication that received a translation, i.e., [(total # caregiver translations to gestures + total # caregiver translations to vocalizations) / (total # infant gestures + total # infant vocalizations)]; c) the proportion of infants' total moving communication that received a verbal response, i.e., [(total #

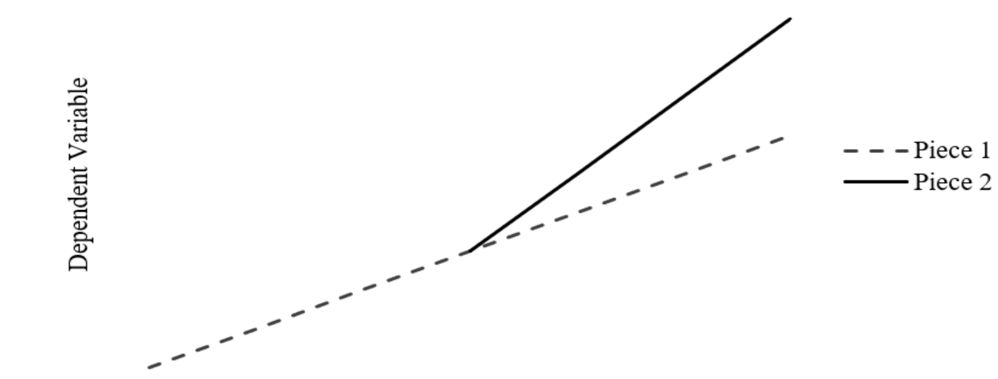
caregiver responses to moving gestures + total # caregiver responses to moving vocalizations) / (total # infant moving gestures + total # infant moving vocalizations)]; and d) the proportion of infants' total stationary communication that received a verbal response, i.e., [(total # caregiver responses to stationary gestures + total # caregiver responses to stationary vocalizations) / (total # infant stationary gestures + total # infant stationary vocalizations)].

2.7 Analytic Approach

This study had two overarching objectives. The first objective was to measure changes in infants' locomotor behavior, object interactions, communication, and caregivers' contingent responses as infants transitioned from crawling to walking. The second objective was to probe whether these changes differed among three HR outcome groups—HR-ASD, HR-LD, and HR-ND infants—and their LR peers. Hierarchical linear modeling (HLM) was used to achieve these objectives. HLM partitions the variance of nested data into within-cluster effects and between-cluster effects. This is well-suited for these data, as time-points are nested within individual infants, and individual infants are nested within risk/outcome groups. At the within-infant level (Level 1), we assessed how time-varying factors (e.g., walking experience) account for variance in dependent variables. At the between-infant level (Level 2), we assessed how time-invariant factors (e.g., outcome group membership) account for variance in infants' intercept and slope terms. An additional advantage is that HLM accommodates missing and unequally spaced data (e.g., Huttenlocher, Haight, Bryk, Seltzer & Lyons, 1991; Singer, 1998). For the present study, 674 of 812 (83.0%) observations were complete. Missingness was substantially greater for HR infants (96% complete for LR, 81% complete for HR), primarily because 7 HR infants were enrolled in the study late, and the frequency of missed visits was much greater among HR infants. However, within the HR group, patterns of missingness did not differ by outcome group (81% complete for HR-ND; 82% complete for HR-LD; 81% complete for HR-ASD). Data were analyzed using Version 7 of HLM for Windows (Raudenbush, Bryk, Cheong, Congdon & du Toit, 2011).

2.7.1 Model Selection

Data analysis began by selecting the best-fitting, most parsimonious model for each dependent variable. A multistep process was carried out to select the appropriate model. For each variable of interest, four unconditional models were calculated (i.e., models with no predictors other than intercept and slope terms). The first was an intercept-only model. An intercept-only model may seem counterintuitive for longitudinal data, but it is the most appropriate when the dependent variable remains stable over time (i.e., it depicts a flat line). Second, an unconditional linear model with TIME as a predictor was fitted. Next, an unconditional quadratic model with TIME and $TIME^2$ predictors was calculated. Finally, an unconditional piecewise linear model was fitted, with PIECE 1 TIME and PIECE 2 TIME included as predictors. A piecewise model estimates growth over time as two pieces, rather than a single continuous variable. PIECE 1 estimates baseline growth in the dependent variable across the entire period (i.e., all 7 timepoints in this study). PIECE 2 estimates linear growth following an inflection point (here, the session prior to walk onset; Figure 1 provides a schematic illustration of how time is coded). A significant PIECE 2 slope denotes an incremental change in linear growth following the inflection point.



Piece 1[a]	-3	-2	-1	0	1	2	3
Piece 2[b]	0	0	0	0	1	2	3

[a]The top row illustrates how Piece 1 was coded. Each cell represents walking experience measured in months, where 0 represents the final crawling-only visit, and 1 represents walk onset (a 1 unit increase is equivalent to an increase of 1 month of walking experience). This variable represents a baseline linear growth.

[b]The bottom row illustrates how Piece 2 was coded. Unlike Piece 1, only months with positive walking experience are included. Thus, this variable represents additional incremental linear growth during walking months only.

Figure 1 Schematic Illustration of the Piece 1 and 2 Time Variables

Next, we compared the fit of each unconditional model. A deviance score was generated for each model, comparing the observed values against the model-predicted values. Model deviance scores were compared using chi-square statistics. Higher-order growth models were selected only if they significantly reduced deviance, and if the additional growth term was significantly greater than zero. In some instances (crawling duration, crawling frequency, moving social bids), piecewise and quadratic models did not significantly differ in their model fit. When this occurred, the model with the lower deviance score was selected. This process led us to select linear, quadratic, and piecewise models to describe growth trajectories.

2.7.2 Final Conditional Models

Final Linear Models. For linear models, Level 1 estimated individual linear growth across the period as a function of TIME. We centered the data at the mid-point, which was the visit prior to walk onset. This point was chosen as the intercept because it marks the very start of the transition to walking. The equation for Level 1 is as follows:

(1) $Y_{ti} = \pi_{0i} + \pi_{1i}*(TIME_{ti}) + e_{ti}$

Here the intercept (π_{0i}) represents the level of the dependent variable of infant *i* at the midpoint. The term π_{1i} represents the linear slope—the rate and direction of change across the period—for infant *i*.

At Level 2, time-invariant variables were included as predictors of the intercept and linear slope. This included a dummy variable for each HR outcome classification group (HR-ND, HR-LD, and HR-ASD); the LR infants served as a reference group. Additionally, to control for differences in age, infants' age at walk onset was included as a predictor on intercept and slope terms. The final Level 2 equations for the final linear model were as follows:

(2) $\pi_{0i} = \beta_{00} + \beta_{01}*(\text{Age at Walk Onset}_i) + \beta_{02}*(ND_i) + \beta_{03}*(LD_i) + \beta_{04} (ASD_i) + r_{0i}$

(3) $\pi_{1i} = \beta_{10} + \beta_{11}*(\text{Age at Walk Onset}_i) + \beta_{12}*(ND_i) + \beta_{13}*(LD_i) + \beta_{14} (ASD_i) + r_{1i}$

Here, coefficients (the β terms) represent the deviation of each HR group from the LR reference group. For instance, β_{00} represents the LR group's score at the intercept, and β_{02} represents the deviation of the HR-ND group (i.e., the intercept for HR-ND infants can be calculated by summing β_{00} and β_{02}). It should be noted that this model tests whether each HR group differs from the LR group; it does *not* allow us to compare the HR groups to one another. To test for differences between HR groups we recalculated the models and rotated the reference group.

Final Quadratic Models. At Level 1, quadratic models estimated individual growth as a function of TIME and TIME^2. Again, we centered the data at the midpoint—the visit prior to walk onset. The equation for Level 1 is as follows:

(1) $Y_{ti} = \pi_{0i} + \pi_{1i}*(TIME_{ti}) + \pi_{2i}*(TIME^2_{ti}) + e_{ti}$

The intercept (π_{0i}) represents an infant *i*'s score at the midpoint. In this quadratic model, the term π_{1i} represents the *instantaneous* linear slope for infant *i*—this term indicates the rate and the direction of change *specifically at the intercept*. The term π_{2i} represents the quadratic growth for infant *i*—i.e. the acceleration or deacceleration over time.

Again, Level 2 included dummy variables for each outcome group (HR-ND, HR-LD, and HR-ASD) as well as infants' age at walk onset as predictors of the intercept, instantaneous linear slope, and quadratic slope. The equations for Level 2 are:

(2) $\pi_{0i} = \beta_{00} + \beta_{01}*(\text{Age at Walk Onset}_i) + \beta_{02}*(ND_i) + \beta_{03}*(LD_i) + \beta_{04}(ASD_i) + r_{0i}$

(3) $\pi_{1i} = \beta_{10} + \beta_{11}*(\text{Age at Walk Onset}_i) + \beta_{12}*(ND_i) + \beta_{13}*(LD_i) + \beta_{14}(ASD_i) + r_{1i}$

(4) $\pi_{2i} = \beta_{20} + \beta_{21}*(\text{Age at Walk Onset}_i) + \beta_{22}*(ND_i) + \beta_{23}*(LD_i) + \beta_{24}(ASD_i) + r_{2i}$

The intercept (π_{0i}), instantaneous linear slope (π_{1i}) and quadratic slope (π_{2i}) are modeled as a function of the between-subject variables—the β terms. These β terms are interpreted as deviations of each outcome group from the reference group. To illustrate, β_{12} represents the HR-ND's deviation from the LR reference group (i.e. the instantaneous linear slope for HR-ND infants can be calculated by summing β_{10} and β_{12}). Again, to examine group-differences among the HR outcome groups, we recalculated each model, rotating the reference group.

Final Piecewise Models. For piecewise models, growth was estimated as a function of two slope terms: PIECE 1 slope (all time points; baseline growth) and PIECE 2 slope (incremental growth after walk onset). Again, we centered the data at the midpoint—the visit prior to walk onset. The equation for Level 1 is as follows:

(1) $Y_{ti} = \pi_{0i} + \pi_{1i}*(\text{PIECE } 1_{ti}) + \pi_{2i}*(\text{PIECE } 2_{ti}) + e_{ti}$

Again, the intercept (π_{0i}) represented infant *i*'s score at the visit prior to walk onset. The Piece 1 slope represents the estimated baseline linear growth rate for infant *i*, and the Piece 2 slope represents the estimated additional incremental growth from the visit prior to walk onset forward for infant *i* (See Figure 1 for a depiction of the coding of piecewise time).

Level 2 predictors were consistent with linear and quadratic models and included dummy variables for outcome groups and infants' age at walk onset. The equations for Level 2 are:

(2) $\pi_{0i} = \beta_{00} + \beta_{01}*(\text{Age at Walk Onset}_i) + \beta_{02}*(\text{ND}_i) + \beta_{03}*(\text{LD}_i) + \beta_{04} (\text{ASD}_i) + r_{0i}$

(3) $\pi_{1i} = \beta_{10} + \beta_{11}*(\text{Age at Walk Onset}_i) + \beta_{12}*(\text{ND}_i) + \beta_{13}*(\text{LD}_i) + \beta_{14} (\text{ASD}_i) + r_{1i}$

(4) $\pi_{2i} = \beta_{20} + \beta_{21}*(\text{Age at Walk Onset}_i) + \beta_{22}*(\text{ND}_i) + \beta_{23}*(\text{LD}_i) + \beta_{24} (\text{ASD}_i) + r_{2i}$

Again, Level 1 model terms (the intercept, Piece 1 slope, and Piece 2 slope) are modeled as a function of the Level 2 between-subject variables. These β terms are interpreted as deviations of each outcome group from the reference group.

3.0 RESULTS

This study had two overarching objectives. First, we investigated the developmental cascade hypothesis—that walk onset corresponds to a cascade of events in which infants locomote more, interact with more objects, produce more gestures and vocalizations, and receive more contingent responses from parents. Second, we tested whether this transition differed among three groups of HR infants who varied in outcome at 36 months: HR-ND, HL-LD, and HR-ASD infants. Following preliminary analyses, we present data relevant to the primary study aims. The first set of analyses models changes in LR and HR infants' locomotion (Aim 1), including mode of locomotion (crawling, cruising, and walking), and functional features of movement (e.g., how often infants approached social partners). Second, we modeled developmental trajectories of LR and HR infants' object interactions during this transition (Aim 2). Next, we analyzed trajectories of LR and HR infants' communication, and the extent to which gestures and vocalizations were moving (paired with locomotion) and directed (paired with gaze to a social partner; Aim 3). Finally, models were fitted to measure trajectories of caregivers' verbal responses as their infant transitioned from crawling to walking; These trajectories were compared across LR and HR outcome groups (Aim 4). Partial correlations between all dependent variables (controlling for age at each session) are included in Appendix A. For all final analyses, the descriptive statistics, model coefficients, and graphical depictions of model estimates are presented in turn. In addition, primary analyses were accompanied by supplemental comparisons when relevant, in order to further probe whether trajectories differed among HR groups (for example, to detect whether HR-ASD infants differed significantly from HR-LD infants).

3.1 Preliminary Analyses

Preliminary analyses were conducted to test whether infants' age at walk onset differed across outcome groups. Descriptive statistics are shown in Table 2. Overall, HR-ASD and HR-LD infants tended to walk later than their peers. A one-way ANOVA uncovered a significant effect of Outcome Group Membership, F (3, 108) = 3.23, $p = 0.025$, and planned contrasts revealed that the HR-LD group was significantly older than the LR group ($p = .033$). There were no other significant differences among groups. To ensure that results of the final conditional models are not influenced by these age differences, infants' age at walk onset was included as a predictor for every model term in all final HLM models.

Table 2 Means and Standard Deviations for Age at Walk Onset by Outcome Group

	LR			HR-ND			HR-LD			HR-ASD		
	M	*SD*	*range*	*M*	*SD*	*range*	*M*	*SD*	*range*	*M*	*SD*	*range*
Age	11.76	1.56	9-15	12.51	1.82	8-17	13.15	1.791	10-17	13.14	1.88	11-16

3.2 Trajectories of Infant Locomotion

The first aim of this research was to measure longitudinal changes in locomotion across the transition to walking by observing infants' use of crawling, cruising, and walking in their home environments across the seven sessions. We also examined changes in infants' social approaches (how often they locomoted to a social partner) and social disengagements (how often they locomoted away from a social partner). Descriptive statistics for all locomotion variables across the four outcome groups are shown below in Table 3. Model coefficients for locomotion variables appear in Table 4 and 5. Because the LR infants served as a reference group, model coefficients for HR groups should be interpreted as deviations from the LR group in their intercept, linear growth, or quadratic growth.

Table 3 Descriptive Statistics for Infant Locomotion Variables

		LR			HR-ND			HR-LD			HR ASD		
	Time	*M*	*sd*	*range*	*M*	*sd*	*range*	*M*	*sd*	*range*	*M*	*sd*	*range*
Crawling duration (secs)	-3	14.08	22.59	0 - 68.48	28.30	34.87	0-128.83	24.17	33.87	0-107.83	21.62	20.89	0-76.98
	-2	26.10	36.39	0-129.45	38.25	40.59	0-154.22	41.00	38.64	0-158.51	28.82	25.77	0-71.61
	-1	33.85	31.63	0-99.50	38.10	37.72	0-155.69	29.41	30.27	0-120.84	55.41	52.30	0-153.80
	0	35.64	30.09	0-117.71	44.83	44.66	0-179.26	42.58	40.01	0-156.95	23.21	30.22	0-94.46
	1	22.18	16.79	0-57.91	27.67	44.34	0-260.26	19.64	19.95	0-60.32	20.20	28.82	2.15-96.94
	2	7.78	9.23	0-34.77	15.04	26.34	0-139.24	9.65	10.18	0-29.32	17.25	23.49	0-71.40
	3	4.18	5.61	0-16.39	4.12	5.06	0-18.92	2.67	5.03	0-12.52	3.56	3.97	0-7.83
Cruising duration (secs)	-3	4.66	18.34	0-91.85	1.17	3.46	0-15.56	1.10	3.37	0-14.63	1.35	4.66	0-16.15
	-2	19.58	58.74	0-260.99	6.17	13.63	0-69.45	3.38	6.86	0-24.30	2.00	3.84	0-10.15
	-1	17.66	37.43	0-143.06	16.95	45.71	0-270.30	5.60	7.22	0-20.05	10.51	20.39	0-70.26
	0	20.89	33.26	0-122.84	21.56	26.20	0-101.71	22.25	28.81	0-94.02	15.55	23.26	0-58.47
	1	33.59	50.80	0-231.93	31.31	49.91	0-237.01	20.18	28.26	0-104.60	32.01	50.96	0-174.27
	2	17.86	39.07	0-192.63	10.26	16.60	0-68.71	10.87	13.20	0-40.08	19.12	23.00	0-73.89
	3	7.46	15.83	0-66.23	12.69	17.70	0-68.42	13.68	15.71	0-49.60	4.12	7.13	0-22.22
Walking duration (secs)	-3	0	0	0-0	0	0	0-0	0.13	0.60	0-2.73	0	0	0-0
	-2	0.51	2.57	0-12.86	0.07	0.47	0-3.22	0.21	0.99	0-4.63	0	0	0-0
	-1	0.17	0.84	0-4.22	0.13	0.86	0-5.73	0.35	1.17	0-4.67	0	0	0-0
	0	1.24	3.25	0-13.78	0.28	1.20	0-7.23	1.50	3.89	0-13.78	0.22	0.73	0-2.41
	1	13.63	28.52	0-122.77	36.08	61.92	0-271.26	38.92	66.21	0-229.49	25.59	39.9	0-107.3
	2	65.99	57.82	0-183.48	87.59	81.65	0-309.96	105.8	110.81	0-404.05	122.8	119.7	0-348.6
	3	109.79	69.84	0-282.66	142.4	115.0	0-398.11	113.2	66.59	21.4-231.4	112.3	77.56	6.1-243.1
Social approach frequency	-3	0.29	0.46	0-1	0.70	1.09	0-4	0.29	0.64	0-2	0.83	1.19	0-3
	-2	0.48	0.87	0-3	0.74	1.02	0-4	1.18	1.59	0-6	0.92	1.12	0-3
	-1	1.20	1.61	0-6	1.52	2.15	0-12	1.36	1.22	0-4	1.77	1.83	0-5
	0	1.46	1.47	0-6	1.98	2.02	0-7	2.13	2.31	0-10	2.00	2.57	0-9
	1	1.68	1.63	0-5	2.18	1.83	0-8	217	2.08	0-6	2.18	2.82	0-9
	2	2.56	2.14	0-9	3.30	2.56	0-10	3.93	3.67	0-11	3.30	2.31	0-7
	3	3.71	2.63	0-12	4.35	3.67	0-16	5.17	4.95	0-18	4.00	3.54	0-11
Social disengage frequency	-3	0.17	0.38	0-1	0.52	0.01	0-3	0.24	0.54	0-2	0.25	0.45	0-1
	-2	0.28	0.74	0-3	0.89	1.23	0-5	0.91	1.15	0-4	0.23	0.60	0-2
	-1	0.88	1.51	0-5	1.14	1.67	0-7	1.18	1.33	0-4	1.23	0.93	0-3
	0	0.92	1.41	0-6	1.66	2.06	0-11	1.63	1.91	0-7	1.18	2.18	0-7
	1	1.48	1.30	0-4	1.71	1.93	0-9	1.26	1.91	0-8	1.55	1.81	0-6
	2	2.20	1.78	0-6	2.58	2.05	0-7	2.21	2.23	0-8	3.10	2.03	0-6
	3	3.12	1.90	0-6	3.15	2.53	0-10	3.33	2.27	0-7	3.11	2.42	0-6

Table 4 Model Estimates of Crawling, Cruising, and Walking Durations

	Crawling duration		Cruising duration		Walking duration	
	Coefficient	s.e.	Coefficient	s.e.	Coefficient	s.e.
Intercept, π_0						
LR intercept, β_{00}	37.23***	5.40	32.44***	5.88	-4.42	2.76
Age at walk onset, β_{01}	1.00	2.13	3.29*	1.66	2.51	0.89
HR-ND, β_{02}	10.21	8.01	-5.21	7.12	0.49	3.63
HR-LD, β_{03}	5.28	8.14	-13.67	8.29	8.20	5.49
HR-ASD, β_{04}	17.97~	10.30	-11.04	0.82	3.42	4.28
Piece 1 slope, π_1						
LR slope, β_{10}	4.48*	2.22	8.37***	2.53	-2.04	1.19
Age at walk onset, β_{11}	-2.05*	0.92	0.87	0.71	1.05	0.37
HR-ND, β_{12}	1.67	3.43	0.90	3.08	0.27	1.58
HR-LD, β_{13}	2.37	3.57	-1.07	3.64	3.56	2.37
HR-ASD, β_{14}	10.45**	4.00	-0.47	4.42	1.56	1.86
Piece 2 slope, π_2						
LR slope, β_{20}	-17.75***	4.00	-16.54***	4.50	37.83***	8.44
Age at walk onset, β_{21}	0.72	1.51	-3.47*	1.38	-1.94	2.45
HR-ND, β_{22}	-5.00	5.85	0.89	5.52	13.99	10.44
HR-LD, β_{23}	-4.25	6.45	6.22	6.57	-3.68	12.62
HR-ASD, β_{24}	-16.34~	8.49	5.25	7.90	3.28	14.50

Note: df = 111; s.e. = standard error; ~p<.10, *p<.05, **p<.01, ***p<.001

3.2.1 Crawling Duration

Duration of infant crawling was modeled using a piecewise linear model. Estimated growth trajectories for groups are depicted in Figure 2, and Figure 3 shows individual infants' estimated trajectories. These figures show that LR infants steadily increased in total time spent crawling until walk onset, after which crawling duration sharply declined. This trend is reflected in the final conditional model. Prior to walk onset, LR infants had significant positive growth in crawling duration (β_{10} = 4.48, SE = 2.22, p = 0.046); they increased by 4.48 seconds each month. After walk onset, LR infants had significant *negative* change in crawling (β_{20} = -17.75, SE = 4.00, p < 0.001); their total crawling duration decreased by 12.24 seconds each month. The HR-

ND and HR-LD groups showed a similar pattern and did not differ significantly from the LR reference group.

HR-ASD infants, on the other hand, displayed a different pattern. Prior to walk onset, they increased by 14.93 seconds of crawling each month, surpassing the LR infants ($\beta_{14} = 10.45$, SE = 4.00, $p = 0.010$; see Figure 2). At the midpoint, HR-ASD infants crawled for a longer duration than any other group, though this difference was not significant ($\beta_{04} = 6.29$, SE = 5.27, $p = 0.24$). After walk onset, they decreased their total crawling time by 19.16 seconds each month; this decline was marginally steeper than the LR group ($\beta_{24} = -16.34$, SE = 8.49, $p = 0.056$).

Although these results reveal how HR-ASD infants differed from the LR reference group, they do not provide information about whether the HR-ASD group differed from the other HR groups. To obtain this information, we reran the HLM model, this time substituting in the HR-ASD infants as the reference group. This allowed us to compare their trajectory to those of the HR-ND and HR-LD groups. Doing so revealed that HR-ASD infants had a significantly steeper increase in total crawling duration prior to walk onset than HR-ND infants ($p = 0.036$). This was marginally steeper than HR-LD infants ($p = 0.065$). However, changes in total crawling time did not differ between groups after walk onset—all HR groups exhibited sharp declines after they attained walk onset.

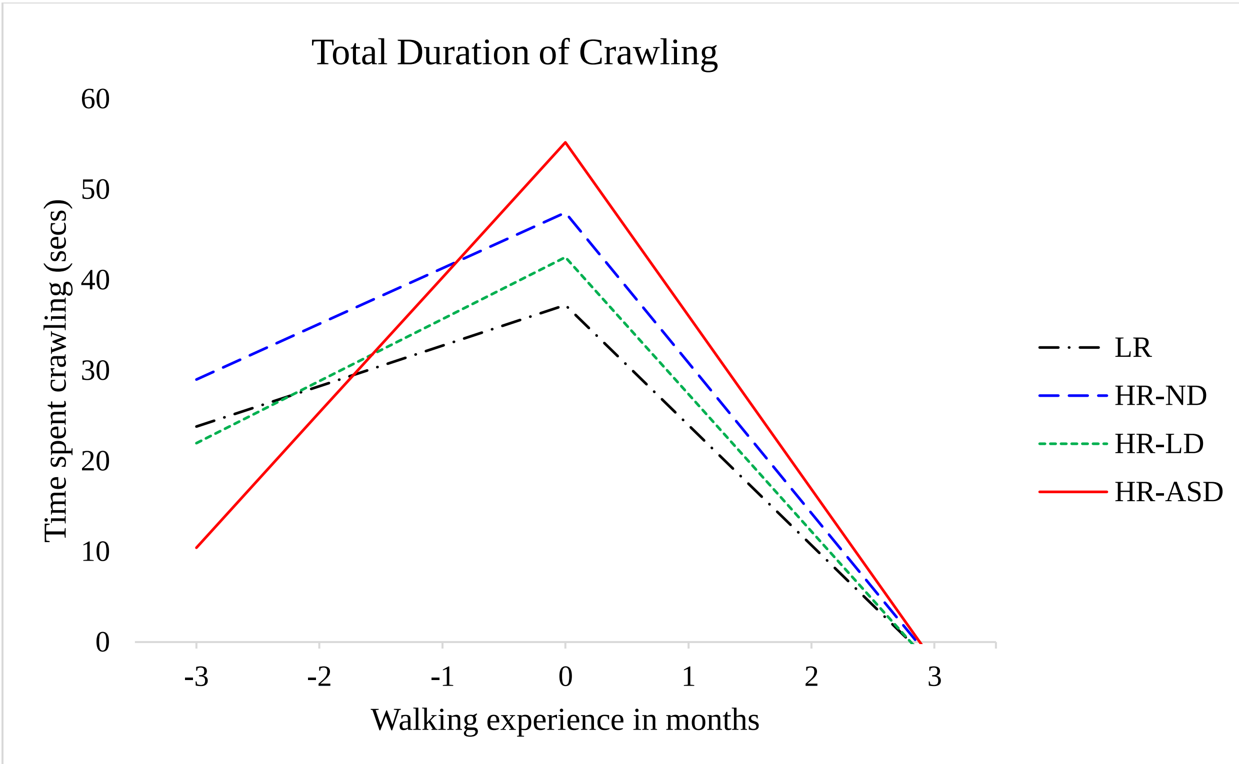


Figure 2 Model Projections of Crawling Duration Over Time

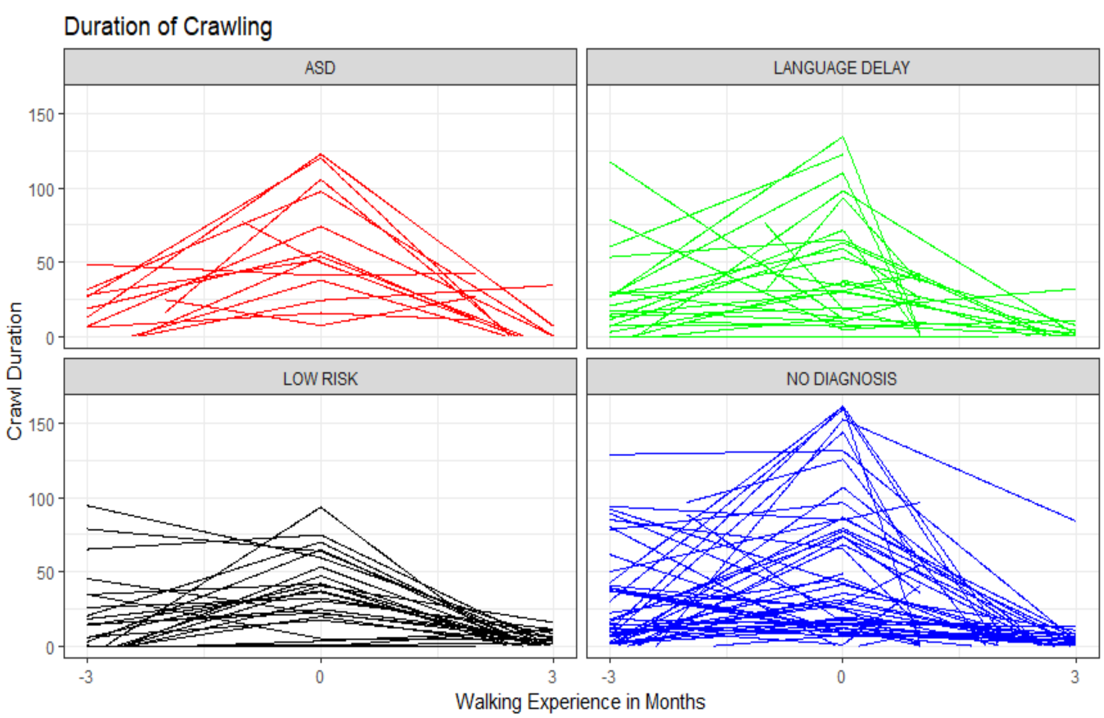


Figure 3 Individual Trajectories of Crawling Duration Over Time

3.2.2 Cruising Duration

Figure 4 depicts the estimated growth trajectories for the total duration of infant cruising, which was again modeled using a piecewise linear model. As can be seen in the figure, cruising durations consistently increased until walk onset, after which there was a decline, presumably as infants began to walk independently. Prior to walk onset, LR infants showed significant positive growth in cruising duration (β_{10} = 8.37, SE = 2.53, $p < 0.001$), increasing by 8.37 seconds each month. Cruising duration peaked at the midpoint (the visit prior to walk onset), as LR infants spent 32.44 seconds cruising during the 10-minute session (β_{00} = 32.44, SE = 5.88, $p < 0.001$). After walk onset, LR infants displayed a significant, negative change in the total time they spent cruising (β_{20} = -16.54, SE = 4.50, $p < 0.001$), decreasing by 8.28 seconds each month. Model coefficients uncovered no significant differences between the HR groups and the LR reference group.

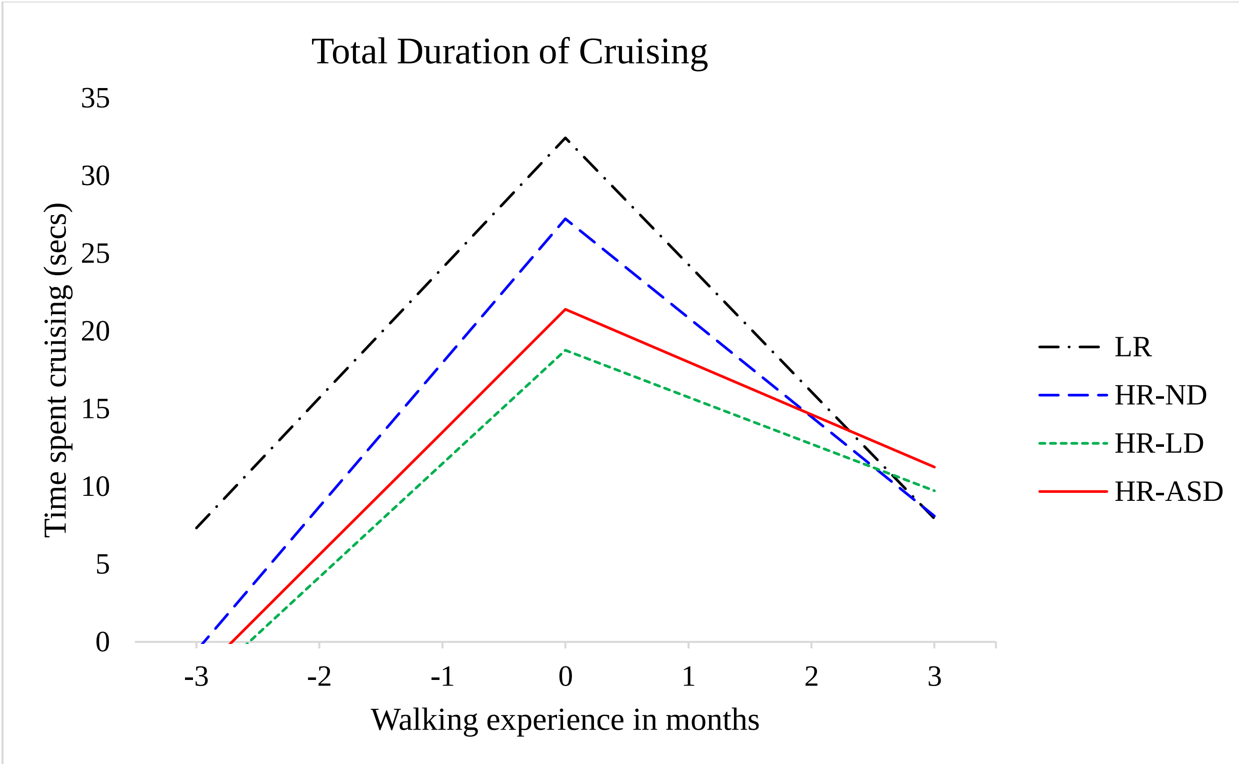


Figure 4 Model Projections of Cruising Duration Over Time

3.2.3 Walking Duration

Estimated trajectories of walking are presented in Figure 5. Prior to parents' report of walk onset, infants almost never walked. However, in infrequent instances, pre-walking infants took short bouts of unsteady steps prior to their designated walk onset. Although we did not code the number of steps, these bouts lasted for short durations: on average, individual walking bouts lasted about 0.25 seconds prior to walk onset. LR infants' walking duration did not change prior to their designated walk onset sessions (walking duration did not differ significantly from 0; $\beta_{10} = -2.04$, SE = 1.19, $p = 0.46$). After walk onset, LR infants had significant positive growth: walking duration increased by 37.83 seconds each month ($\beta_{20} = 37.83$, SE = 8.44, $p < 0.001$). By the final session, LR infants spent 102.91 seconds walking—approximately 17% of the total session time. Model coefficients indicated that there were no significant differences in the trajectories of LR and HR groups.

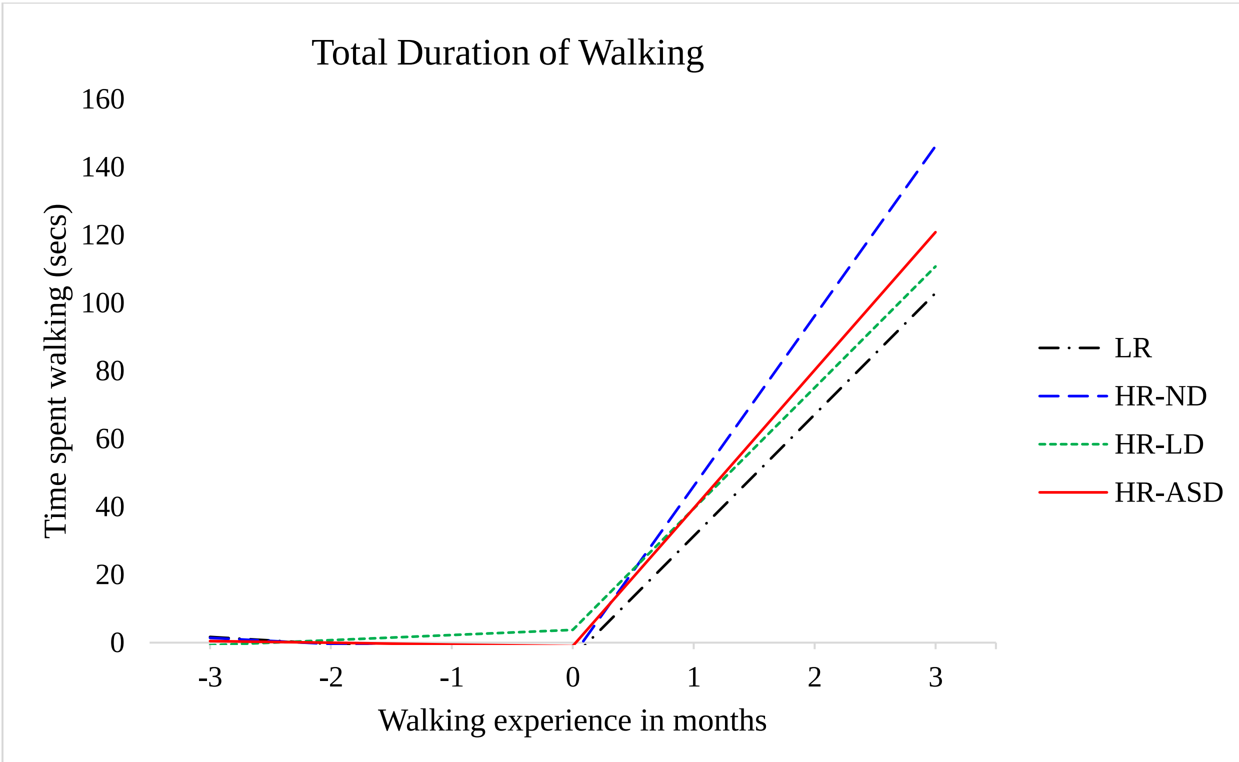


Figure 5 Model Projections of Walking Duration Over Time

3.2.4 Approaching & Disengaging from Social Partners

Trajectories for the total numbers of infants' social approaches (locomotion to a social partner) and disengagements (locomotion away from a social partner) were fitted with linear models. Coefficients are presented below in Table 5, and descriptive statistics appear in Table 3.

Table 5 Model Estimates for Infant Social Approaches and Disengagements

	Social Approach Frequency Coefficient	s.e.	Social Disengagement Frequency Coefficient	s.e.
Intercept, π_0				
LR intercept, β_{00}	1.63***	0.22	1.31***	0.15
Age at walk onset, β_{01}	0.02	0.06	0.04	0.06
HR-ND, β_{02}	0.39	0.27	0.29	0.20
HR-LD, β_{03}	0.43	0.32	0.11	0.24
HR-ASD, β_{04}	0.42	0.38	0.10	0.25
Linear slope, π_1				
LR slope, β_{10}	0.43***	0.11	0.40***	0.07
Age at walk onset, β_{11}	-0.10***	0.03	-0.07***	0.02
HR-ND, β_{12}	0.10	0.12	-0.03	0.09
HR-LD, β_{13}	0.21	0.16	-0.003	0.10
HR-ASD, β_{14}	0.11	0.18	0.14	0.11

Note: df = 111; s.e. = standard error; ~p<.10, *p<.05, **p<.01, ***p<.001

Estimated trajectories for the frequency of social approaches (i.e., the number of locomotion bouts in which an infant approached a social partner) are presented in Figure 6. Initially, infants almost never approached social partners. LR infants exhibited modest but significant positive growth over time (β_{11} = 0.43, SE = 0.11, $p < 0.001$), increasing each month by 0.43 social approaches. At the midpoint, LR infants approached social partners approximately 1.63 times during the 10-minute session (β_{10} = 1.63, SE = 0.22, $p < 0.001$). This trajectory was consistent across HR outcome groups; there were no significant differences between LR and HR infants.

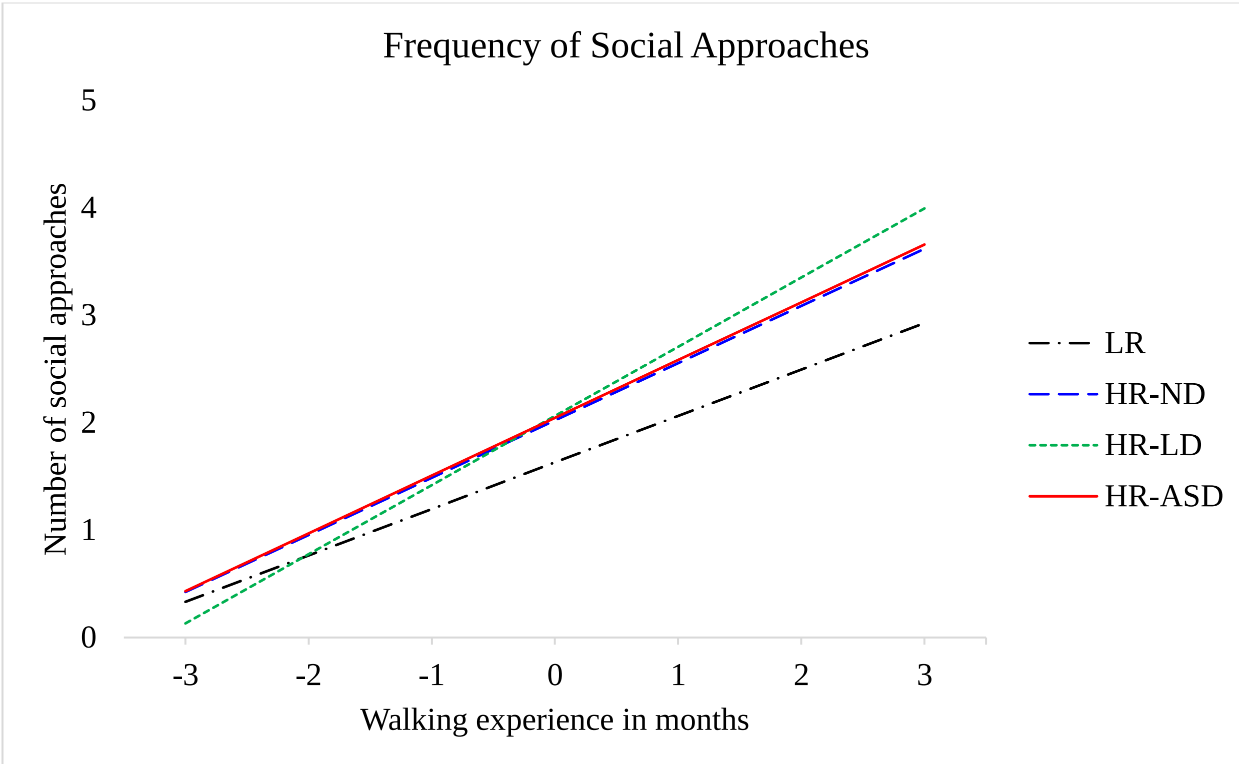


Figure 6 Model Projections of Social Approaches Over Time

The frequency of social disengagements (i.e., the number of locomotion bouts in which an infant locomoted away from a social partner) followed an almost identical trajectory. Estimated trajectories are shown below in Figure 7. At the first session, LR infants rarely disengaged from social partners. They exhibited positive linear growth, increasing by 0.40 social disengagements each month ($\beta_{10} = 0.40$, SE = 0.07, $p < 0.001$). At the midpoint, they disengaged from social partners 1.31 times during the 10-minute session ($\beta_{00} = 1.31$, SE = 0.15, $p < 0.001$). This pattern was consistent among the HR infants, and model coefficients indicated no significant differences between LR and HR outcome groups.

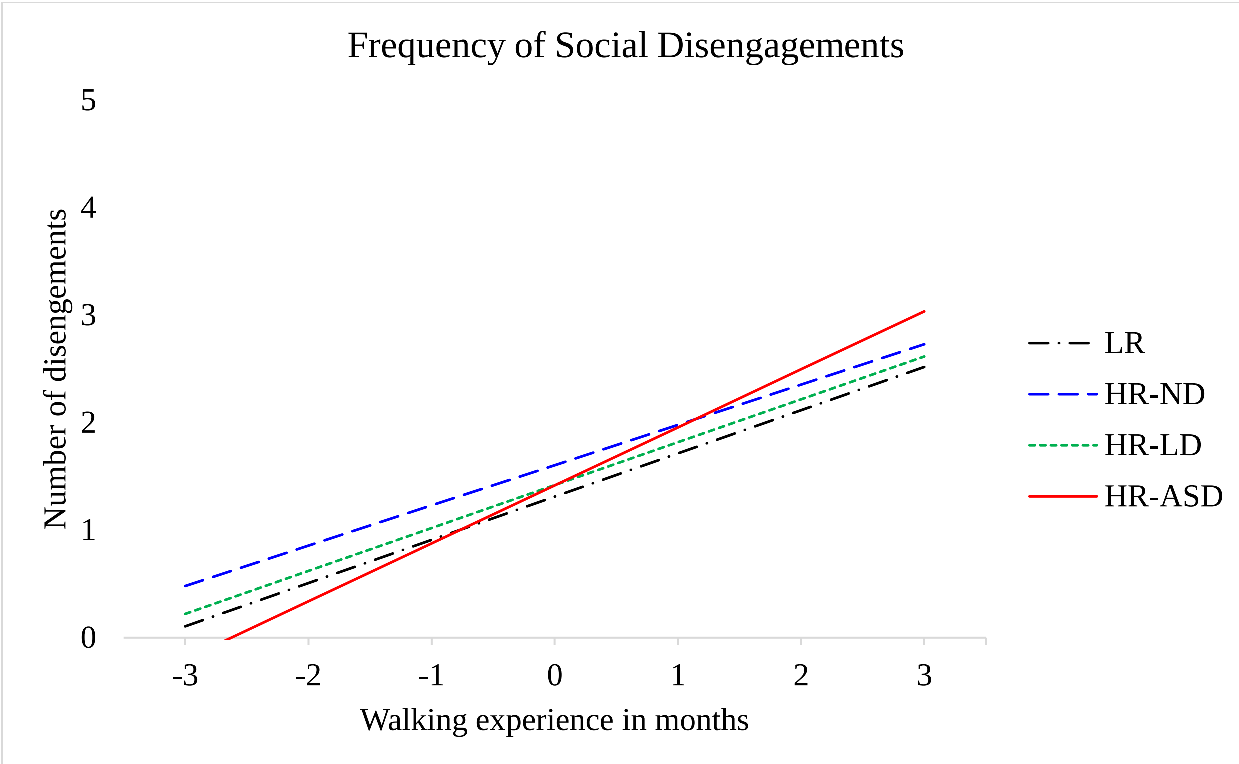


Figure 7 Model Projections of Social Disengagements Over Time

3.2.5 Summary

Parent report of walk onset did indeed correspond to a transformation in infant locomotion. All infants—regardless of risk status or outcome—displayed a pattern of inflection at walk onset: there was a robust upswing in independent walking, while crawling and cruising declined. However, it should be noted that infants did continue to crawl and cruise even after months of walking experience. In addition, infants increasingly approached and disengaged from their caregivers. Thus, a back-and-forth pattern of social interaction emerged over time.

The hypothesis that walking would be reduced for HR-ASD infants was not supported. Overall, HR-ASD infants' locomotion trajectories were similar to their peers (although there was a deviation in their crawling prior to walk onset). This finding is inconsistent with past findings of atypical walking development in ASD and may be due to methodological differences. Past research has used chronological age as the basis of comparison. Here, data were organized around the onset of walking. Therefore, the question we addressed here—which differs subtly from past work—is *when HR-ASD infants do walk, does their developmental progression differ*? Overall, trajectories of locomotion were similar to LR and HR peers, though future work should address this question using more finely-tuned measures.

3.3 Trajectories of Infant Object Interactions

The second study aim was to measure trajectories of object interactions across the transition to walking. The analyses reported below assessed: a) the frequency of locomotion bouts to retrieve distal objects (object approaches); b) the frequency of carrying objects; and c) the total number of unique objects that infants interacted with (object variety). Descriptive statistics are provided in Table 6. For object approaches and variety, linear models were found to fit the data best. Object carrying was best described by a quadratic growth model. All model coefficients appear in Table 7.

Table 6 Descriptive Statistics for Infant Object Interaction Variables

	Time	LR			HR-ND			HR-LD			HR ASD		
		M	*sd*	*range*	*M*	*sd*	*range*	*M*	*sd*	*range*	*M*	*sd*	*range*
Frequency of object approaches	-3	0.75	1.23	0-4	2.13	2.86	0-11	2.00	3.02	0-10	1.25	1.36	0-4
	-2	1.96	2.46	0-8	3.02	3.72	0-14	3.77	3.53	0-11	2.85	2.48	0-6
	-1	3.84	2.67	0-9	3.57	3.64	0-16	4.59	3.66	0-14	3.77	2.83	0-9
	0	3.92	3.30	0-13	4.59	4.30	0-17	4.75	5.43	0-25	2.91	2.43	0-8
	1	4.64	3.83	0-13	5.42	5.36	0-24	4.91	5.49	0-24	3.27	3.82	0-13
	2	5.52	3.97	0-17	6.36	4.35	1-18	4.50	3.55	0-12	8.50	5.13	3-21
	3	7.63	4.71	0-20	8.96	5.96	0-23	9.17	6.73	0-19	5.56	3.64	1-11
Frequency of object carrying	-3	0.33	1.44	0-7	1.07	2.52	0-12	0	0	0-0	0	0	0-0
	-2	0.80	2.00	0-9	1.22	2.59	0-9	0.95	1.68	0-6	0.08	0.28	0-1
	-1	1.92	4.01	0-14	2.55	5.19	0-25	1.05	1.76	0-6	0.85	1.73	0-6
	0	2.13	4.30	0-18	3.25	6.08	0-25	1.67	3.07	0-12	0.91	1.14	0-3
	1	2.76	3.55	0-12	4.42	7.64	0-34	4.13	5.86	0-21	1.64	3.04	0-10
	2	5.12	4.51	0-16	8.76	8.79	0-31	8.36	9.44	0-29	6.80	7.42	0-20
	3	11.13	9.20	0-32	13.69	11.28	0-39	11.50	8.01	3-27	9.56	10.1	0-32
Total object variety	-3	4.46	2.28	1-9	6.48	3.61	1-15	5.86	3.55	0-13	6.58	3.34	2-13
	-2	5.08	3.16	1-12	6.76	3.45	2-17	8.00	4.80	3-21	8.46	3.15	2-14
	-1	5.88	3.03	1-13	6.84	3.80	2-17	9.00	3.99	2-17	6.92	4.05	1-16
	0	7.96	3.68	3-17	8.23	4.54	1-19	8.79	3.59	3-19	5.82	2.99	1-11
	1	8.16	3.63	2-16	7.49	4.43	0-16	8.30	4.48	1-19	5.27	2.61	2-9
	2	8.64	3.65	3-17	9.00	4.37	2-20	8.64	5.42	0-21	9.90	2.81	7-14
	3	8.33	3.47	2-18	10.35	5.17	3-27	9.75	4.67	4-17	7.78	4.32	3-18

Table 7 Model Estimates for Infant Object Approaches, Carrying, and Variety

	Object Approach Frequency		Object Carrying Frequency		Total Object Variety	
	Coefficient	s.e.	Coefficient	s.e.	Coefficient	s.e.
Intercept, π_0						
LR intercept, β_{00}	4.32***	0.39	2.55***	0.69	7.17***	0.42
Age at walk onset, β_{01}	0.34*	0.16	0.76***	0.19	0.29*	0.13
HR-ND, β_{02}	0.51	0.53	0.88	0.85	0.63	0.54
HR-LD, β_{03}	0.38	0.67	-0.38	0.99	1.11~	0.66
HR-ASD, β_{04}	-0.68	0.58	-1.27	1.19	-0.13	0.60
Linear slope, π_1						
LR slope, β_{10}	0.89***	0.13	1.35***	0.34	0.64***	0.09
Age at walk onset, β_{11}	-0.13*	0.05	-0.12	0.10	-0.12**	0.04
HR-ND, β_{12}	0.07	0.20	0.53	0.43	-0.12	0.16
HR-LD, β_{13}	0.02	0.22	0.37	0.52	-0.15	0.22
HR-ASD, β_{14}	-0.02	0.25	0.08	0.59	-0.44~	0.24
Quadratic slope, π_2						
LR slope, β_{20}	---	---	0.28*	0.13	---	---
Age at walk onset, β_{21}			-0.12**	0.04		
HR-ND, β_{22}			0.12	0.47		
HR-LD, β_{23}			0.07	0.20		
HR-ASD, β_{24}			0.04	0.23		

Note: df = 111; s.e. = standard error; ~p<.10, *p<.05, **p<.01, ***p<.001

3.3.1 Object Approaches

Estimated growth trajectories for the frequency of object approaches are shown in Figure 8. As can be seen, LR infants rarely approached objects during the first session. The LR group displayed significant positive growth (β_{10} = 0.89, SE = 0.13, $p < 0.001$), with an increase of 0.89 object approaches each month. At the final timepoint LR infants approached objects approximately 7 times during the 10-minute session. Model estimates indicated that trajectories for HR infants did not differ from that of LR infants.

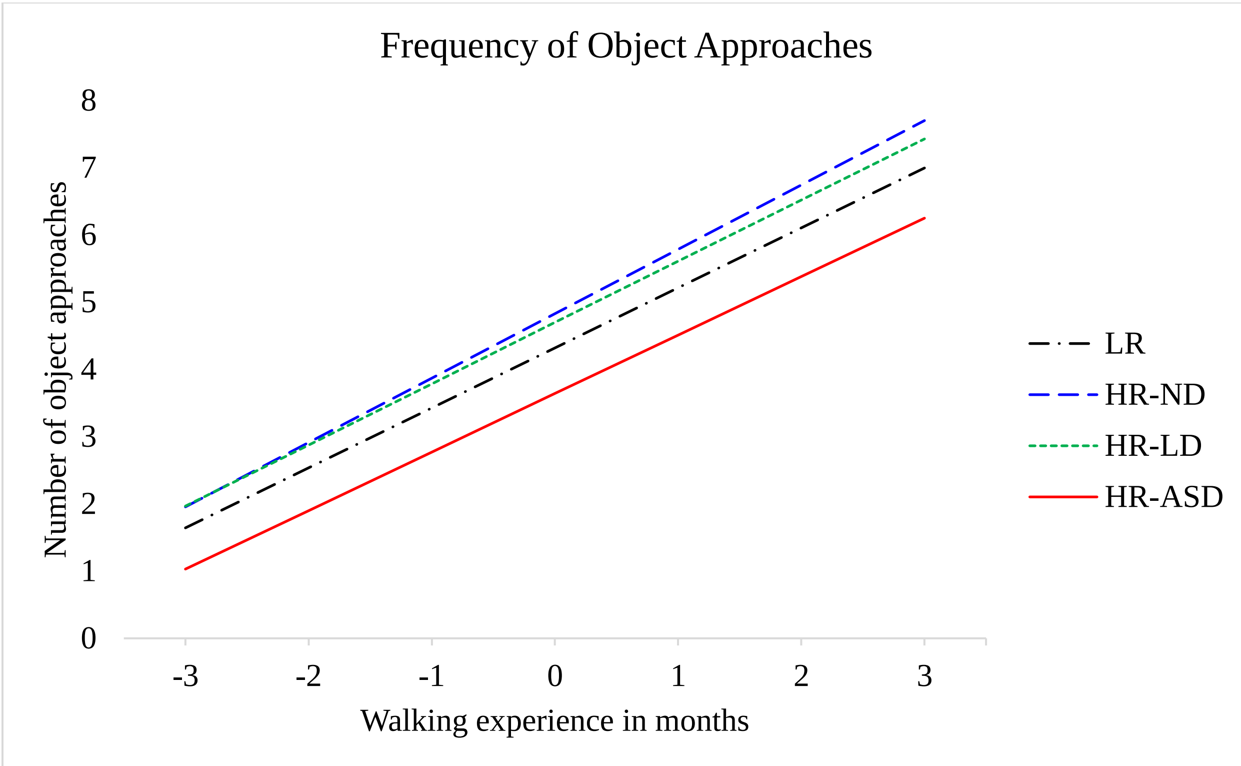


Figure 8 Model Projections of Object Approaches Over Time

3.3.2 Carrying Objects

Figure 9 shows the estimated growth trajectories for the frequency of object carrying bouts. As is evident, LR infants displayed positive and accelerating growth in object carrying. At the midpoint, the LR reference group carried objects approximately 2.55 times (β_{00} = 2.55, SE = 0.69, p < 0.001). Additionally, their growth accelerated by 0.28 object carries each month (β_{20} = 0.28, SE = 0.13, p = 0.029), such that by the final visit LR infants frequently carried objects, doing so approximately 17 times over the 10-mintue session. No differences were revealed between the HR groups and the LR reference group.

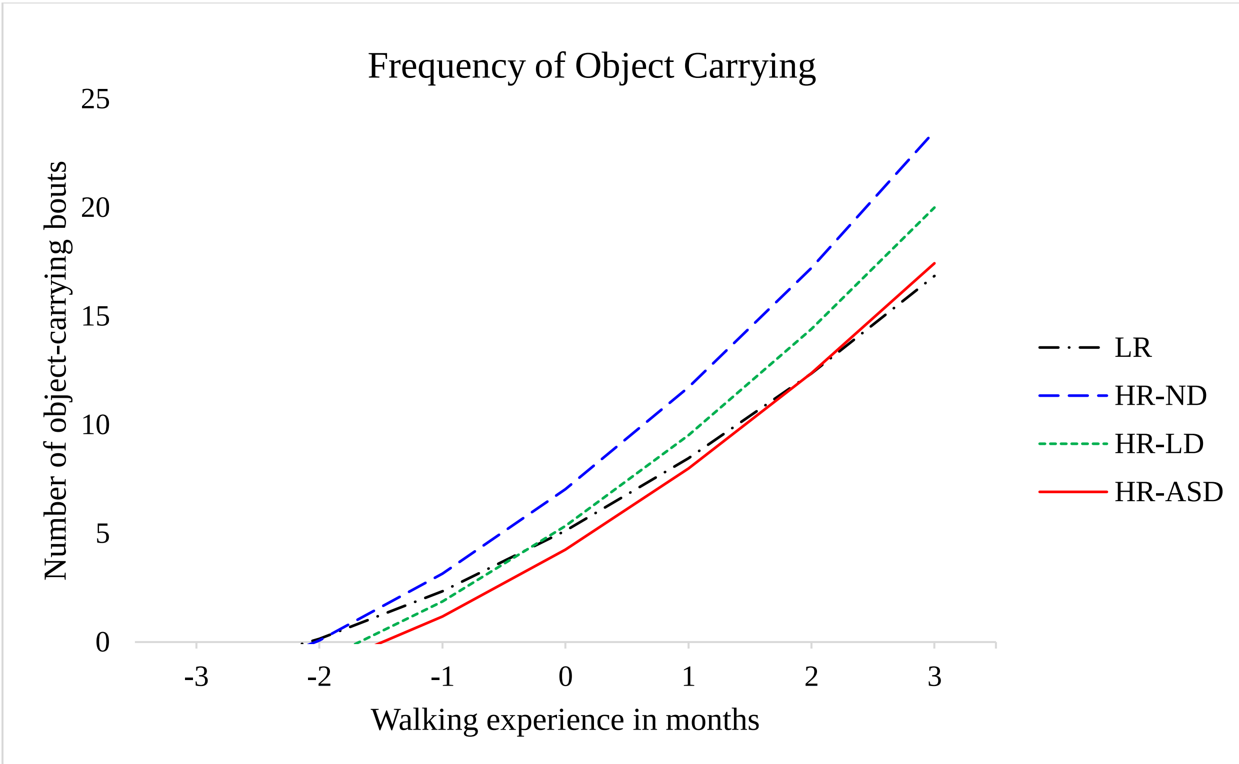


Figure 9 Model Projections for Object Carrying Over Time

3.3.3 Object Variety

Estimated growth trajectories for object variety (i.e., number of different objects contacted by infants) are shown in Figure 10. LR infants displayed positive linear growth in object variety (β_{10} = 0.64, SE = 0.09, p < 0.001), increasing the number of different objects they accessed by 0.64 each month. The model estimated that at the first session, LR infants interacted with 5.25 different objects; this escalated to 9.09 by the last session. There were no significant differences between LR and HR groups. However, HR-ASD showed a marginally significant attenuation in growth compared to LR infants (β_{14} = -0.44, SE = 0.24, p = 0.07). In fact, model estimates showed HR-ASD infants increased by only 0.20 different objects each month, and interacted with 7.64 objects at the final session.

Model coefficients tell us whether the HR-ASD group trajectory differed from the LR reference group, but they provide no information as to whether the linear growth experienced by HR-ASD was significantly greater than zero. Given HR-ASD infants' pattern of attenuation, we decided to further probe whether their linear growth was significant. To do this, we reran the model, this time substituting the HR-ASD infants as the reference group. This revealed that the number of objects HR-ASD infants interacted with did not change significantly over time (p = 0.34). Conversely, both HR-ND and HR-LD infants showed significant positive growth in the variety of objects they interacted with ($p < 0.001$; $p = 0.007$ respectively).

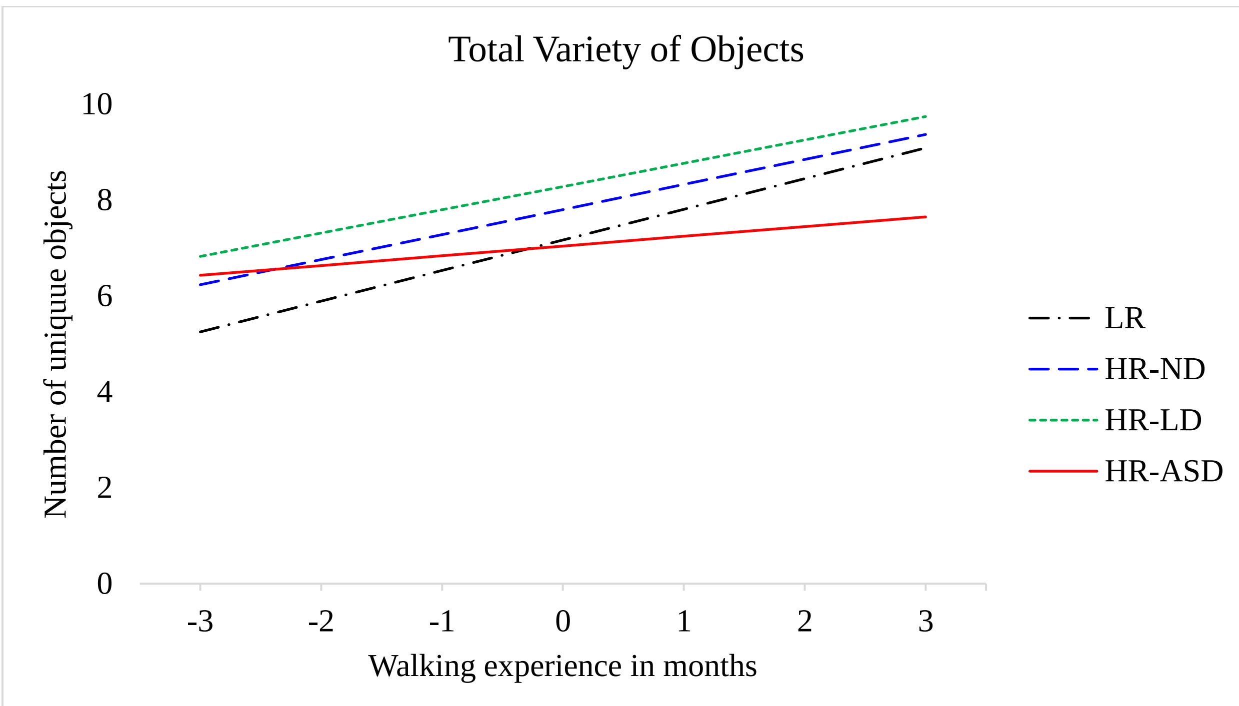


Figure 10 Model Projections for Object Variety Over Time

3.3.4 Summary

We predicted that over this transition, the LR, HR-ND, and HR-LD groups would increasingly locomote to pick up distal objects, carry objects more frequently, and play with more objects. These hypotheses were supported. We replicated past findings showing that during this period, LR, HR-ND, and HR-LD infants increasingly locomoted to pick up out-of-reach objects and carried objects while locomoting. Further, we extended past work by showing that the *variety* of objects with which LR, HR-ND, and HR-LD infants interact increases over time. Although HR-ASD infants did not differ in their frequency of object approaches or object carrying bouts, they did not change in the variety of objects they accessed over time.

3.4 Trajectories of Infant Gestures and Vocalizations

The third study aim was to measure trajectories of infant gestures and vocalizations across the transition to walking in LR and HR outcome groups. Additionally, we examined the extent to which these behaviors were coupled with gaze to caregivers ("directed") and locomotion ("moving"). Descriptive statistics are shown in Table 8, and model coefficients are presented in Table 9. For gestures and moving communication, piecewise linear models were selected to model growth over time. Linear models were the best fit for all other communication variables.

Table 8 Descriptive Statistics for Infant Communication Variables

		LR			HR-ND			HR-LD			HR ASD		
	Time	*M*	*sd*	*range*	*M*	*sd*	*range*	*M*	*sd*	*range*	*M*	*sd*	*range*
Gesture Frequency	-3	2.08	2.59	0-11	3.04	4.59	0-22	4.24	7.52	0-35	1.83	2.13	0-7
	-2	3.44	4.20	0-16	3.61	3.21	0-15	5.09	7.24	0-31	3.69	2.21	1-7
	-1	4.48	5.69	0-20	3.66	3.18	0-13	4.00	17.80	0-18	3.69	2.72	0-8
	0	4.63	4.69	0-17	4.18	3.60	0-17	4.46	4.07	0-14	3.00	2.68	0-10
	1	6.40	4.61	1-17	6.07	6.86	2-89	6.39	5.57	0-21	4.27	3.07	1-10
	2	7.96	5.67	1-26	8.36	6.28	0-40	5.29	4.45	0-16	3.70	4.60	0-15
	3	10.75	8.43	0-31	7.24	5.75	1-22	6.09	4.16	1-14	5.00	3.94	2-15
Vocalization Frequency	-3	22.08	14.93	2-57	29.20	17.23	6-98	22.76	15.91	1-59	23.08	22.17	2-81
	-2	18.48	12.48	1-46	31.83	17.84	7-70	34.50	14.74	4-62	22.77	13.07	5-46
	-1	28.88	19.07	1-67	33.02	17.85	2-84	28.14	17.80	5-75	25.62	20.85	6-70
	0	36.33	16.92	10-78	35.64	17.93	2-89	33.71	22.66	3-95	37.18	18.72	5-66
	1	35.48	20.13	3-77	40.60	25.72	5-122	40.17	24.02	5-104	24.73	7.98	11-42
	2	42.28	18.36	9-87	49.39	23.42	15-104	36.86	18.95	7-70	21.50	11.41	7-42
	3	46.38	19.37	17-81	43.00	21.69	17-91	42.45	18.77	11-67	33.00	16.56	6-52
Directed Communication Frequency	-3	6.54	4.14	1-17	10.11	8.64	0-43	7.57	9.01	0-37	9.67	9.63	0-36
	-2	7.72	6.91	0-27	11.09	8.74	0-43	12.82	8.09	2-32	7.54	5.47	2-18
	-1	12.36	11.91	1-41	11.50	7.74	0-28	10.64	10.93	0-46	12.46	11.24	0-41
	0	12.75	8.02	0-32	13.55	8.98	0-37	13.88	11.73	2-43	14.00	12.78	0-42
	1	15.72	8.74	3-31	15.49	11.99	1-64	15.57	13.85	2-48	10.18	5.69	3-21
	2	18.64	9.02	1-38	19.21	13.03	2-55	16.07	17.74	2-31	7.90	7.92	0-26
	3	20.71	10.71	4-47	18.28	12.49	5-54	18.64	11.08	3-38	13.22	6.42	4-22
Moving Communication Frequency	-3	1.33	2.53	0-11	3.61	5.10	0-19	2.24	4.22	0-17	0.58	0.90	0-3
	-2	2.84	5.15	0-23	5.59	6.47	0-26	5.59	6.72	0-22	3.38	3.25	0-9
	-1	5.48	5.54	0-20	6.64	7.15	0-37	4.64	4.89	0-20	4.23	5.09	0-18
	0	7.88	10.79	0-51	7.18	8.26	0-38	9.92	9.78	0-37	11.55	9.30	0-26
	1	10.68	10.87	0-41	15.36	20.43	0-103	12.87	14.73	0-65	8.27	7.06	1-25
	2	15.80	12.96	0-43	19.64	17.04	1-84	16.07	17.74	0-66	10.70	10.29	0-35
	3	21.96	13.75	4-51	24.48	20.82	083	21.36	11.86	2-39	12.22	8.03	0-23

Table 9 Model Estimates for Infant Communication Variables

	Gesture Frequency		Vocalization Frequency		Directed Communication Frequency		Moving Communication Frequency	
	Coefficient	s.e.	Coefficient	s.e.	Coefficient	s.e.	Coefficient	s.e.
Intercept, π_0								
LR intercept, β_{00}	6.37***	0.64	34.41***	2.07	14.27***	1.05	10.21***	1.23
Age at walk onset, β_{01}	0.90**	0.30	1.67~	0.86	0.87*	0.40	1.27~	0.67
HR-ND, β_{02}	-0.60	0.70	4.11	2.68	0.41	1.28	2.02	1.62
HR-LD, β_{03}	-1.37	1.02	-1.07	3.28	-1.37	1.02	-0.66	1.80
HR-ASD, β_{04}	-2.99***	0.90	-8.54**	3.24	-3.91**	1.49	-3.53~	1.85
Piece 1 slope, π_1								
LR slope, β_{10}	0.84***	0.23	4.58***	0.74	2.52***	0.33	2.21**	0.68
Age at walk onset, β_{11}	0.05	0.08	0.004	0.23	0.11	0.10	0.17	0.20
HR-ND, β_{12}	-0.27	0.30	-1.24	0.97	-7.45	0.48	-0.63	0.81
HR-LD, β_{13}	-0.55	0.51	-1.73	1.08	-1.01*	0.51	0.22	1.03
HR-ASD, β_{14}	-0.25	0.38	-3.61**	1.15	-2.13***	0.62	1.21	1.02
Piece 2 slope, π_2								
LR slope, β_{20}	1.37*	0.57	---	---	---	---	2.16*	1.35
Age at walk onset, β_{21}	0.32~	0.18					-0.31	0.57
HR-ND, β_{22}	-0.12	0.69					2.95	1.82
HR-LD, β_{23}	-0.76	0.83					-1.20	2.22
HR-ASD, β_{24}	-0.79*	0.88					-5.85**	2.01

Note: df = 111; s.e. = standard error; ~p<.10, *p<.05, **p<.01, ***p<.001

3.4.1 Gestures

Figure 11 shows the estimated trajectories for the frequency of infants' gesture production. In addition, individual infants' trajectories are shown in Figure 12. As evidenced in these figures, LR infants display additional incremental growth after walk onset. This pattern is confirmed by model estimates. Prior to walk onset, LR infants show significant positive baseline growth (β_{10} = 0.84, SE = 0.23, p < 0.001), increasing by 0.84 gestures each month. After walk onset, there was additional incremental growth *above and beyond their baseline growth* (β_{20} = 1.37, SE = 0.57, p = 0.018). Gestures increased by a rate of 2.21 gestures each month after walk onset (0.84 gestures per month baseline growth + 1.37 gestures per month additional incremental growth). From the first to final session, LR infants escalated from 3.8 to 13.0 gestures in the 10-minute session.

Model coefficients revealed no differences between the LR reference group and HR-ND and HR-LD groups. However, the model does not provide information about whether these groups also experience enhanced growth following walk onset. To investigate this further, we re-ran the model twice, with HR-ND and HR-LD each serving as the reference group. Consistent with LR infants, the HR-ND group displayed additional incremental growth after walk onset, above and beyond their baseline growth rate (p = 0.014). Therefore, neurotypically developing infants regardless of risk status exhibited an inflection in gesture growth at walk onset. In contrast, HR-LD infants did not experience significant additional growth in gesture production after walk onset (i.e., their rate of change after walk onset did not differ from their baseline rate of change, p = 0.39).

Figure 11 shows that HR-ASD infants produced the fewest gestures of any group, and they displayed a substantially flatter trajectory of gesture production. At the midpoint, HR-ASD infants gestured significantly less frequently than the LR reference group (β_{04} = -2.99, SE = 0.90, p < 0.001). In addition, after walk onset HR-ASD infants' slope significantly diverged from that of the LR infants (β_{24} = -1.79, SE = 0.88, p = 0.045). While LR infants added 2.21 gestures each month after walk onset, HR-ASD infants added only 0.17 gestures per month.

In order to compare the HR-ASD infants to other HR outcome groups, we reran the model with HR-ASD infants serving as the reference group. This confirmed that HR-ASD infants had a significantly different trajectory than HR-ND infants: HR-ASD infants gestured significantly less often than HR-ND infants at the intercept (p = 0.007) and had significantly reduced growth after walk onset (p = 0.05). However, there were no significant differences in the trajectories of HR-ASD and HR-LD infants.

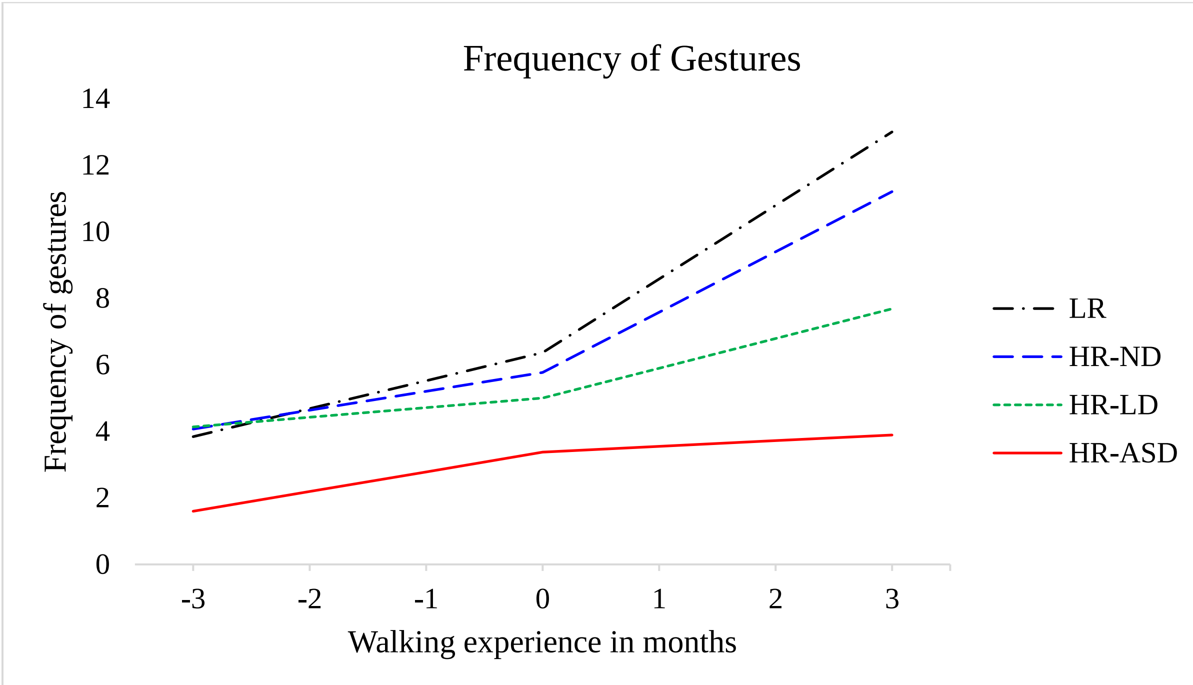


Figure 11 Model Projections for Infant Gestures Over Time

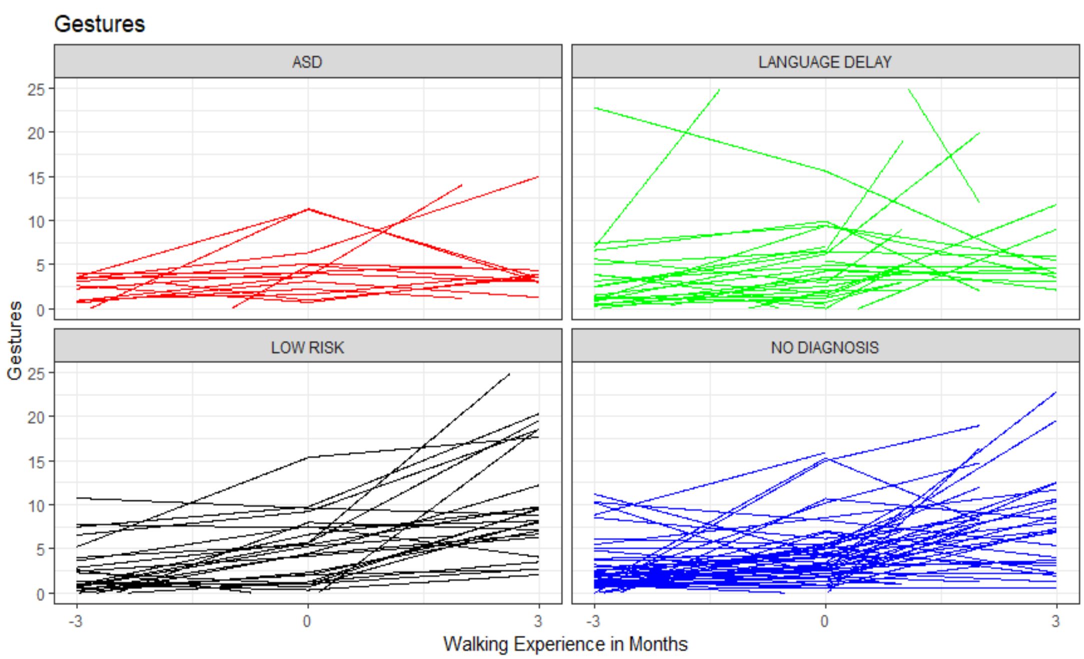


Figure 12 Individual Trajectories of Infant Gestures Over Time

3.4.2 Vocalizations

Estimated growth trajectories for the frequency of vocalizations[3] are presented in Figure 13. The LR reference group demonstrated significant positive growth in vocalization frequency over time (β_{01} = 4.58, SE = 0.74, $p < 0.001$), increasing by 4.58 vocalizations each month. This constituted a substantial change over time: LR infants increased from 20.7 to 48.1 vocalizations from the first to final session—more than doubling their volubility. Trajectories for HR-ND and HR-LD infants did not differ from the LR reference group.

As is apparent in Figure 13, the HR-ASD infants vocalized far less often. At the midpoint, they produced 8.54 fewer vocalizations than LR infants (β_{04} = -8.54, SE = 3.24, p = 0.01). Moreover, linear growth was significantly reduced for the HR-ASD group (β_{14} = -3.61, SE = 1.15, p = 0.002). While LR infants increased by 4.58 vocalizations each month, HR-ASD infants only increased by 0.96 vocalizations per month. The gap between groups amplified over time, such that by the final session HR-ASD infants vocalized almost 30 fewer times in 10 minutes than the LR infants.

In light of this difference, we re-ran the model with the HR-ASD infants as the reference group. This served to compare the trajectory of HR-ASD infants to those of the other HR groups.

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[3]We initially planned to examine infants' word production separately from non-word vocalizations. However, the base rates of words were extremely low. Eighty infants did not produce any words in any session. Of the remaining 36 infants, 19 produced words only during the final session. Given the severity of positive skew, infants' word-vocalizations were collapsed with their non-word vocalizations.

At the intercept, HR-ASD infants vocalized significantly less often than both HR-ND and HR-LD infants ($p < 0.001$, $p = 0.034$ respectively). HR-ASD infants showed significantly reduced linear growth compared to HR-ND infants ($p = 0.031$), but their linear growth did not differ significantly from that of HR-LD peers ($p = 0.10$).

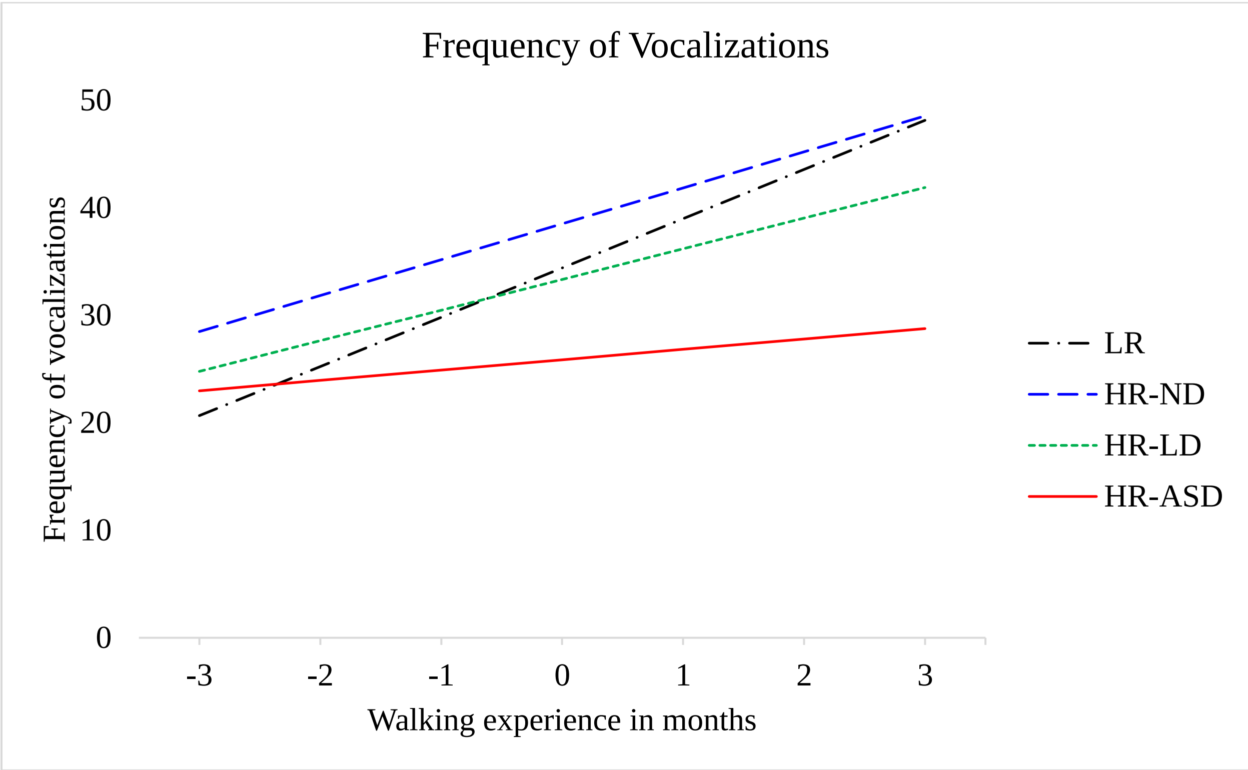

Figure 13 Model Projections for Infant Vocalizations Over Time

3.4.3 Directed Communication

Estimated growth trajectories for the frequency of directed communicative behaviors (i.e., gestures and vocalizations that were paired with gaze to the caregiver) are presented below in Figure 14. The LR reference group displayed significant positive growth over time ($\beta_{10} = 2.52$, SE = 0.33, $p < 0.001$), with an increase of 2.52 directed behaviors each month. At the midpoint, LR infants produced 14.27 directed communicative behaviors in the 10-minute session (β_{00} =

14.27, SE = 1.05, $p < 0.001$). There were no significant differences between HR-ND and LR infants.

In contrast, HR-LD and HR-ASD infants showed diverging trajectories of directed behaviors. Compared to the LR reference group, HR-LD infants showed reduced linear growth ($\beta_{13} = -1.01$, SE = 0.51, $p = 0.049$); but they did not differ at the intercept ($\beta_{03} = -1.37$, SE = 1.02, $p = 0.42$). Compared to the LR reference group, HR-ASD infants showed reduced linear growth ($\beta_{14} = -2.13$, SE = 0.62, $p < 0.001$), and produced 3.91 fewer directed communicative behaviors at the intercept ($\beta_{04} = -3.91$, SE = 1.49, $p = 0.01$). This same pattern was also found when comparing HR-ASD and HR-ND infants: groups differed in both their intercept and slope terms (p's = 0.003, 0.029).

Finally, we compared model terms for HR-ASD and HR-LD infants. This comparison revealed marginally reduced growth in directed communication for HR-ASD infants compared to HR-LR infants ($p = 0.07$).

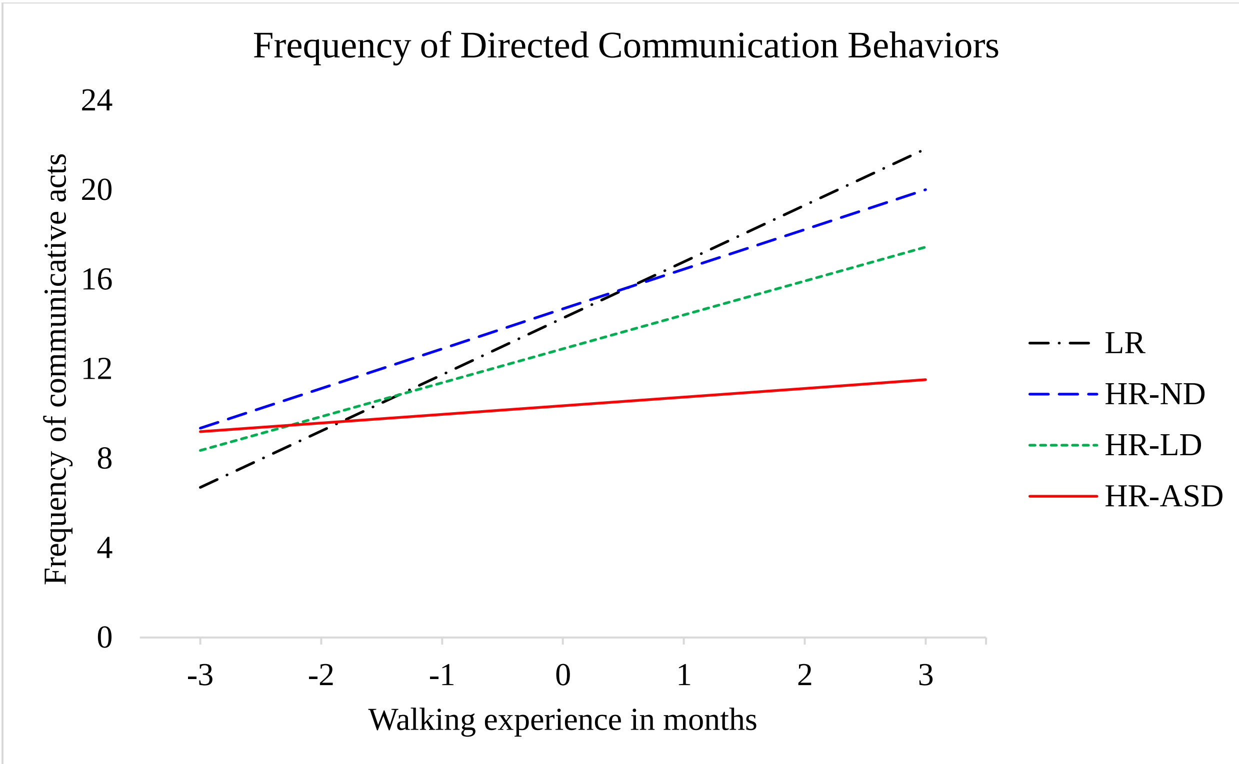

Figure 14 Model Projections for Directed Communication Over Time

3.4.4 Moving Communication

Figure 15 displays growth trajectories of moving communicative behaviors (i.e., gestures and vocalizations that were paired with locomotion) and Figure 16 shows individual infants' estimated trajectories. As can be seen, LR infants showed additional incremental growth in the frequency of moving communicative behaviors after walk onset. This is reflected in the final model estimates. Before walk onset, LR infants displayed significant positive baseline growth in moving behaviors (β_{10} = 2.21, SE = 0.68, p = 0.002), increasing by 2.21 behaviors each month. After walk onset, LR infants displayed significant additional incremental growth in moving behaviors, above and beyond their baseline slope (β_{20} = 2.16, SE = 1.30, p = 0.02). After walk onset, LR infants increased by 4.37 moving behaviors each month (2.21 baseline growth per month + an additional 2.16 behaviors per month). Model estimates for LR infants did not differ from those for the HR-ND or HR-LD groups.

Although the HR-ND and HR-LD groups did not differ from the LR reference group, we wanted to investigate whether walk onset was accompanied by additional growth in moving communication for these groups. To test this, we re-ran the model twice, substituting HR-ND and then HR-LD infants as the reference group. In doing so, we discovered that HR-ND infants also displayed significant additional growth in moving communication after walk onset ($p < 0.001$), while HR-LD infants did not ($p = 0.62$).

HR-ASD infants showed a different growth trajectory of moving communication compared to the LR reference group. Prior to walk onset, linear growth did not differ between the HR-ASD and LR groups ($\beta_{14} = 1.21$, SE = 1.01, $p = 0.24$). After walk onset, HR-ASD infants displayed significantly reduced growth in moving communication ($\beta_{24} = -5.85$, SE = 2.01, $p = 0.004$). In fact, after walk onset HR-ASD infants declined by 0.23 moving behaviors each month.

In light of HR-ASD infants' reduced growth trajectory, we re-ran the model substituting the HR-AD group as the reference group. This permitted comparison of HR-ASD infants to the other HR outcome groups. HR-ASD infants showed significantly less growth in moving behaviors after walk onset than HR-ND infants ($p < 0.001$), and marginally less growth than HR-LD infants ($p = 0.052$).

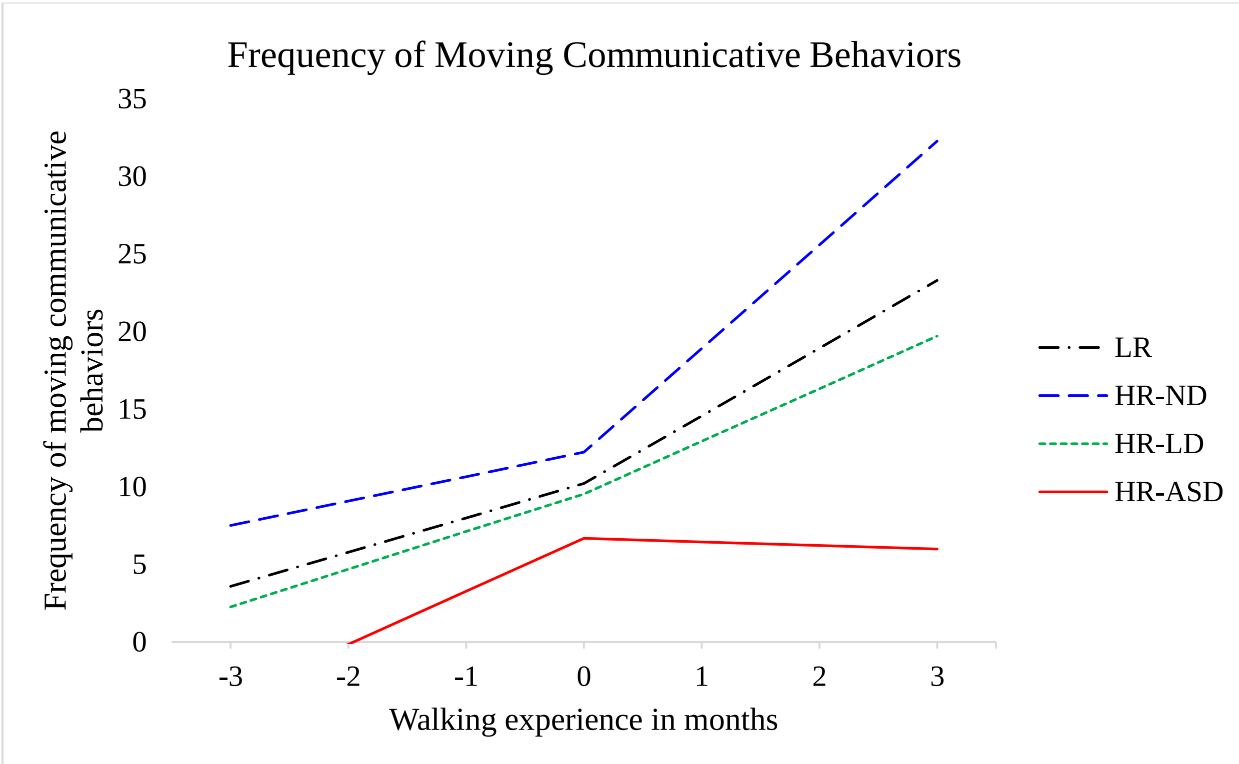

Figure 15 Model Projections of Moving Communication Over Time

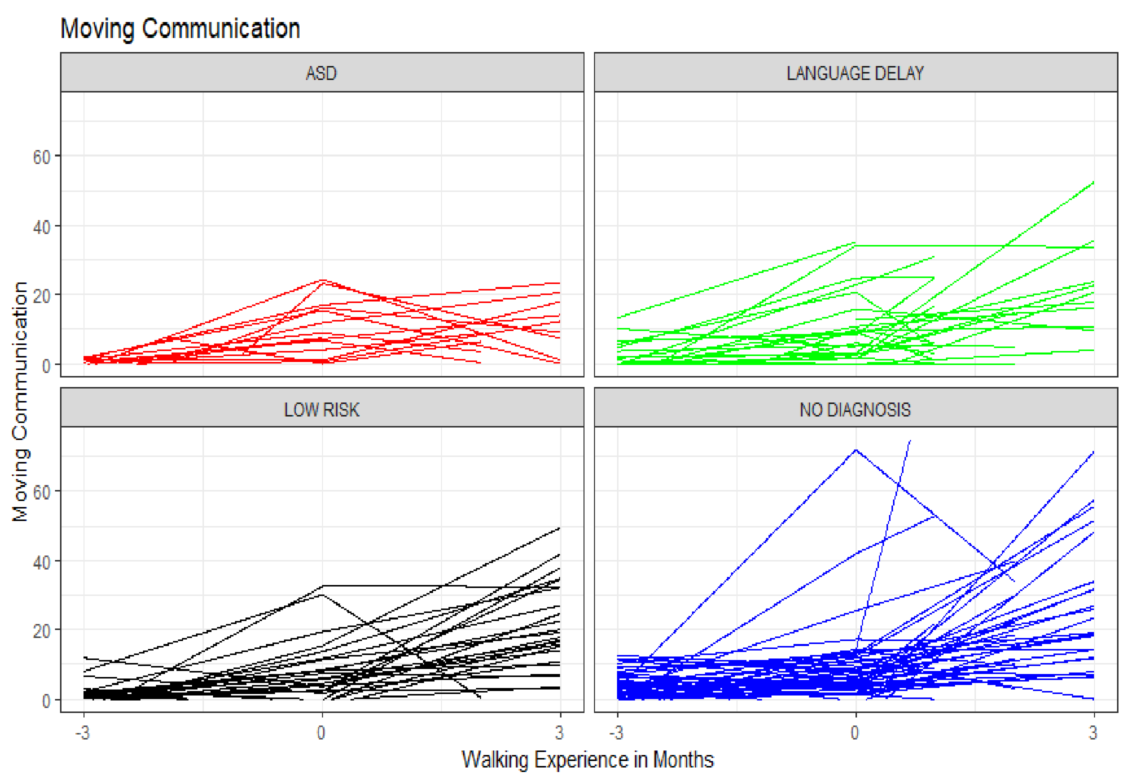

Figure 16 Individual Trajectories of Moving Communication Over Time

3.4.5 Summary

To summarize, LR and HR-ND infants' communication changed dramatically during the transition from crawling to walking. Walk onset was a point of inflection for growth in gestures and in moving communication. Further, vocalization production and directed communication increased consistently over time. The comparison of infant communication between the first and final session is stark: neurotypically developing infants (both LR and HR) *more than doubled the frequencies of every communication variable*.

HR-LD infants showed similar, but attenuated patterns of communication development compared to LR infants. In particular, gesture production was reduced among HR-LD infants, which is consistent with previous findings (e.g., Iverson et al., 2017). Notably, HR-ASD infants deviated the furthest from LR infants. They demonstrated significantly flatter growth on all communication variables relative to LR infants, and did *not* show increased growth after walk onset on either gesture production or moving communication, as their LR and HR-ND peers did. However, it is important to note that while HR-ASD infants tended to show the least growth in communication variables over time, they differed only modestly from HR-LD infants. HR-ASD and HR-LD groups did not differ in their trajectories of gesture or vocalization production. Differences in moving and directed communicative behaviors between HR-ASD and HR-LD groups were only marginally significant. This suggests that while communicative development is atypical in ASD, it may not be specific enough to distinguish infants with ASD for other atypically developing infants.

3.5 Trajectories of Caregiver Responses to Infant Communication

The final study aim was to measure growth trajectories of caregivers' contingent responses to infant communication. Specifically, we modeled changes in verbal responses, responses that contained translations, as well as responses specifically to infants' moving and stationary communicative behaviors. Table 10 presents descriptive statistics for all caregiver response variables. As discussed in the Methods, response variables were calculated as proportions of infants' communicative behaviors. This controlled for the fact that caregivers of HR-LD and HR-ASD infants had fewer opportunities to respond because their infants produced fewer gestures and vocalizations. Linear models were the most appropriate models for all caregiver response variables, and model coefficients are shown in Table 11.

Table 10 Descriptive Statistics for Caregiver Response Variables

		LR			HR-ND			HR-LD			HR ASD		
	Time	*M*	*sd*	*range*	*M*	*sd*	*range*	*M*	*sd*	*range*	*M*	*sd*	*range*
Proportion of infant communication that received a caregiver response	-3	0.18	0.19	0-0.7	0.25	0.24	0-0.9	0.20	0.22	0-0.9	0.20	0.29	0-1
	-2	0.28	0.24	0-0.81	0.27	0.19	0-0.7	0.30	0.25	0-0.8	0.35	0.29	0-0.96
	-1	0.26	0.22	0-0.63	0.30	0.21	0-0.82	0.25	0.23	0-0.82	0.37	0.19	0-0.71
	0	0.28	0.16	0-0.64	0.32	0.22	0-0.92	0.34	0.24	0-0.8	0.24	0.30	0-0.88
	1	0.44	0.19	0-0.77	0.35	0.23	0-0.96	0.38	0.20	0-0.8	0.37	0.17	0-0.68
	2	0.45	0.16	0.2-0.7	0.44	0.24	0-0.89	0.33	0.25	0-0.8	0.25	0.21	0-0.67
	3	0.44	0.20	0-0.75	0.41	0.22	0.13-0.9	0.37	0.15	0.2-0.6	0.42	0.30	0.16-1
Proportion of infant communication that received a caregiver translation	-3	0.01	0.03	0-0.11	0.05	0.08	0-0.48	0.01	0.04	0-0.15	0.07	0.19	0-0.67
	-2	0.03	0.06	0-0.29	0.03	0.05	0-0.16	0.05	0.09	0-0.38	0.03	0.05	0-0.17
	-1	0.03	0.06	0-0.23	0.05	0.06	0-0.22	0.04	0.04	0-0.11	0.05	0.07	0-0.24
	0	0.05	0.06	0-0.19	0.06	0.08	0-0.38	0.03	0.04	0-0.16	0.02	0.04	0-0.1
	1	0.08	0.08	0-0.30	0.08	0.13	0-0.77	0.04	0.05	0-0.20	0.03	0.06	0-0.18
	2	0.10	0.09	0-0.34	0.13	0.15	0-0.58	0.03	0.06	0-0.16	0.03	0.04	0-0.14
	3	0.09	0.09	0-0.45	0.08	0.07	0-0.23	0.05	0.05	0-0.15	0.11	0.15	0-0.46
Proportion of infant moving communication that received a caregiver response	-3	0.20	0.21	0-0.5	0.33	0.35	0-1	0.14	0.18	0-0.4	0.47	0.51	0-1
	-2	0.48	0.36	0-1	0.30	0.31	0-1	0.25	0.27	0-1	0.30	0.42	0-1
	-1	0.29	0.27	0-1	0.29	0.29	0-1	0.20	0.25	0-0.89	0.32	0.28	0-0.7
	0	0.22	0.24	0-1	0.34	0.30	0-1	0.34	0.35	0-1	0.14	0.17	0-0.5
	1	0.47	0.17	0.2-0.8	0.40	0.29	0-1	0.43	0.26	0-1	0.45	0.26	0-1
	2	0.53	0.28	0-1	0.44	0.27	0-1	0.32	0.24	0.06-0.8	0.37	0.26	0-0.7
	3	0.50	0.25	0-1	0.46	0.27	0-1	0.48	0.17	0.2-0.7	0.40	0.29	0-1
Proportion of infant stationary communication that received a caregiver response	-3	0.18	0.19	0-0.67	0.24	0.25	0-0.88	0.20	0.22	0-0.88	0.19	0.28	0-1
	-2	0.24	0.30	0-0.80	0.27	0.21	0-0.77	0.30	0.25	0-0.87	0.35	0.28	0-0.9
	-1	0.24	0.26	0-0.63	0.31	0.22	0-0.85	0.25	0.25	0-0.86	0.39	0.21	0-0.7
	0	0.27	0.25	0-0.75	0.31	0.25	0-0.94	0.32	0.28	0-0.82	0.25	0.32	0-0.8
	1	0.44	0.21	0-0.86	0.34	0.25	0-0.96	0.36	0.23	0-0.81	0.35	0.18	0-0.7
	2	0.44	0.17	0.17-0.7	0.43	0.30	0-0.94	0.34	0.29	0-0.83	0.10	0.44	0-0.7
	3	0.49	0.23	0-0.81	0.37	0.24	0-0.81	0.30	0.13	0.07-0.5	0.42	0.32	0-1

Table 11 Model Estimates for Caregiver Response Variables

	Responses		Translations		Responses to Moving Communication		Responses to Stationary Communication	
	Coefficient	s.e.	Coefficient	s.e.	Coefficient	s.e.	Coefficient	s.e.
Intercept, π_0								
LR intercept, β_{00}	0.36***	0.02	0.07***	0.009	0.39***	0.03	0.34***	0.03
Age at walk onset, β_{01}	0.02**	0.01	0.02*	0.006	0.01	0.01	0.03***	0.01
HR-ND, β_{02}	-0.01	0.03	0.01	0.011	-0.02	0.04	-0.00	0.03
HR-LD, β_{03}	-0.04	0.03	-0.03**	0.012	-0.08	0.04	-0.04	0.04
HR-ASD, β_{04}	-0.04	0.05	-0.03	0.020	-0.05	0.06	-0.05	0.05
Linear slope, π_1								
LR slope, β_{10}	0.05***	0.01	0.018	0.003	0.05***	0.01	0.054***	0.009
Age at walk onset, β_{11}	0.01	0.002	0.003*	0.001	0.00	0.00	0.008**	0.003
HR-ND, β_{12}	-0.02~	0.01	-0.002	0.004	-0.02	0.02	-0.020~	0.011
HR-LD, β_{13}	-0.02	0.01	-0.015***	0.004	-0.01	0.02	-0.026~	0.014
HR-ASD, β_{14}	-0.04*	0.02	-0.017*	0.008	-0.03	0.02	-0.050**	0.003

Note: df = 111; s.e. = standard error; ~p<.10, *p<.05, **p<.01, ***p<.001

3.5.1 Caregiver Verbal Responses

The estimated growth trajectories are depicted below in Figure 17. As is evident in the figure, caregivers of LR infants showed significant positive growth in the proportion of infant communication behaviors they verbally responded to (β_{10} = 0.053, SE = 0.008, p < 0.001); they responded to an additional 5% of infants' communicative behaviors each month. The accumulated growth over time was substantial: initially caregivers responded to 19.9% of infant behaviors, and this rose to 51.8% at the final session. Growth trajectories for HR-ND and HR-LD caregivers did not significantly differ from the LR reference group.

Conversely, caregivers of HR-ASD infants displayed reduced positive growth in verbal responses (β_{14} = -0.035, SE = 0.015, p = 0.018). Each month, caregivers of HR-ASD infants responded to additional 1.7% of infants' communicative behaviors. By the final session, they responded to 36.7% of infant behaviors. To test whether caregivers of HR-ASD infants differed from caregivers of HR-ND and HR-LD infants, we re-ran this model with a HR-ASD reference group. Growth trajectories of verbal responses did not significantly differ among caregivers of HR-ASD, HR-ND, and HR-LD infants.

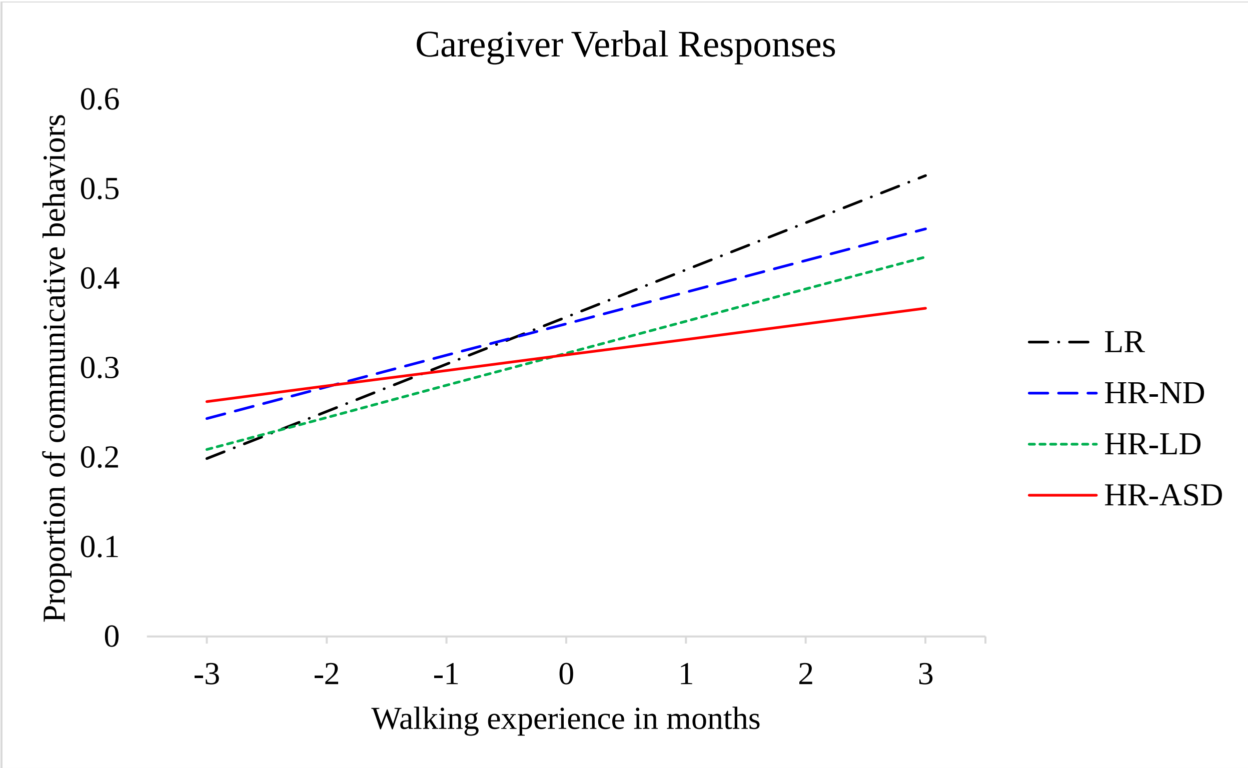

Figure 17 Model Projections of Caregiver Responses Over Time

3.5.2 Caregiver Translations

Growth trajectories for caregiver responses containing translations (a label corresponding to the target of an infant gesture or vocalization; e.g., "Do you want your ball?") are displayed below in Figure 18. Caregivers of LR infants demonstrated positive linear growth in the proportion of infant communicative behaviors that they responded with translations to (β_{10} =

0.0182, SE = 0.003, $p < 0.001$); they responded with a translation to an additional 1.8% of infant communicative behaviors each month. By the final session, caregivers of LR infants provided translations to 12.5% of infants' communicative behaviors. Caregivers of HR-ND infants displayed a nearly identical growth trajectory, and did not differ significantly from the LR reference group.

As seen in Figure 18, caregivers of HR-ASD and HR-LD infants displayed flatter trajectories of translations than the LR reference group. Linear growth was significantly reduced for HR-LD ($\beta_{13} = -0.0147$, SE = 0.004, $p < 0.001$) and HR-ASD caregivers ($\beta_{14} = -0.0168$, SE = 0.008, $p = 0.036$) relative to the LR reference group. In light of these differences, we re-ran the model twice, with caregivers of HR-LD and HR-ASD respectively serving as the reference groups. Both groups displayed significantly flatter growth than HR-ND caregivers ($p = 0.007$ for HR-LD caregivers; $p = 0.023$ for HR-ASD caregivers). Moreover, neither group showed significant change in translations over time ($p = 0.41$ for HR-LD caregivers; $p = 0.85$ for HR-ASD caregivers). Growth trajectories of translations did not differ between HR-LD and HR-ASD groups.

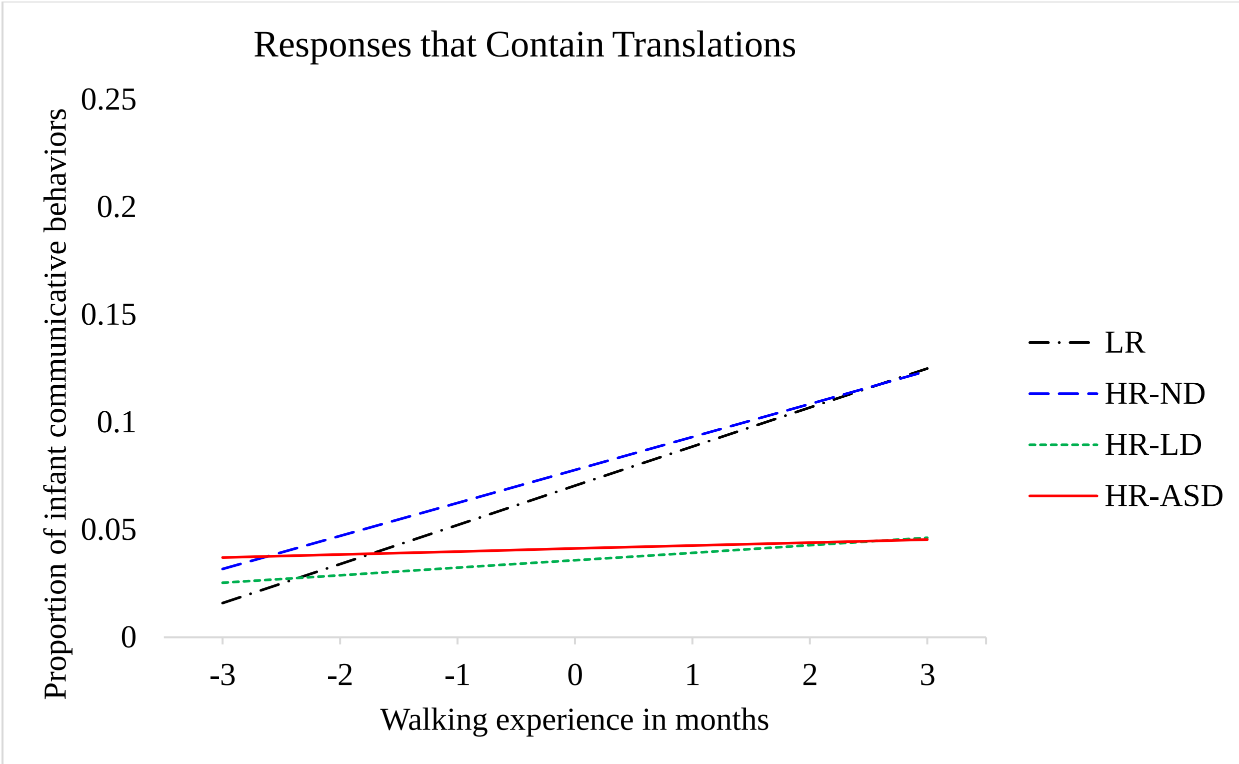

Figure 18 Model Projections of Caregiver Translations Over Time

3.5.3 Caregiver Responses to Infants' Moving and Stationary Communication

The final set of analyses measured caregiver verbal responses to infants' moving and stationary communicative behaviors in turn. Growth trajectories for verbal responses to moving behaviors are displayed in Figure 19. Caregivers of LR infants showed significant positive growth in their responses to moving behaviors over time (β_{10} = 0.05, SE = 0.014, $p < 0.001$). Each month, caregivers of LR infants responded to an additional 5% of infants' moving behaviors. At the first timepoint, caregivers of LR infants responded to 23.7% of moving behaviors. This grew to 53.4% by the final session. There were no differences in the growth trajectories of LR and HR outcome groups.

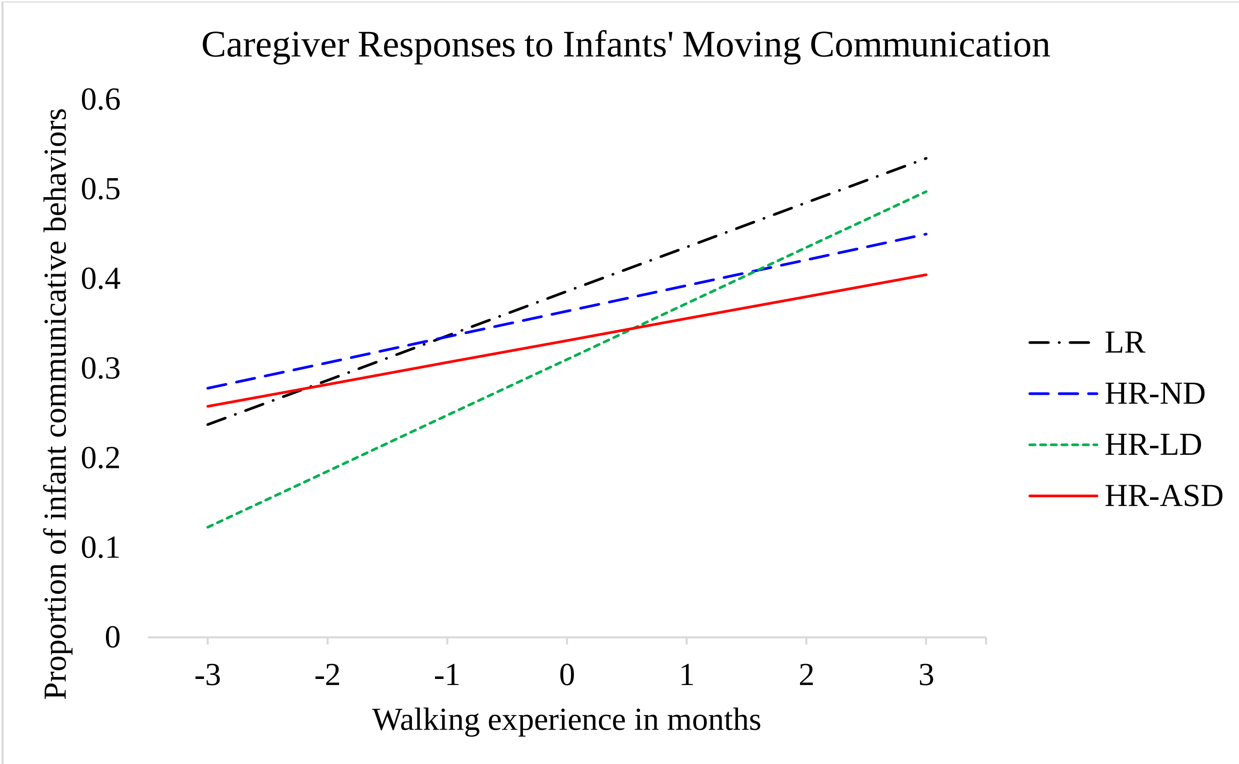

Figure 19 Model Projections of Caregiver Responses to Moving Communication Over Time

Estimated growth trajectories of caregiver responses to infants' stationary communicative behaviors are depicted in Figure 20. For caregivers of LR infants, responses to stationary behaviors followed a notably similar trajectory as responses to moving behaviors. LR caregivers displayed significant positive growth (β_{10} = 0.05, SE = 0.014, $p < 0.001$); each month they responded to an additional 5% of infants' stationary behaviors. At the first session, caregivers of LR infants responded to 18.2% of stationary behaviors; this grew to 50.5% by the last session. Caregivers of HR-ND and HR-LD infants displayed a marginal reduction in linear growth for their responses to stationary behaviors relative to the LR reference group (β_{12} = -0.019, SE = 0.011, p = 0.085; β_{13} = -0.026, SE = 0.014, p = 0.069).

The estimated growth trajectory for caregivers of HR-ASD infants was significantly attenuated (β_{14} = -0.05, SE = 0.016, p = 0.003) compared to the LR reference group. In fact, growth was essentially null, as caregivers of HR-ASD infants increased responses to stationary behaviors by only 0.4% each month. The deviation between LR and HR-ASD caregivers widened over time, such that by the final session HR-ASD caregivers were responding to approximately 20% fewer stationary behaviors than LR caregivers.

Finally, to test whether growth trajectories differed across HR outcome groups, we reran the model with HR-ASD infants serving as the reference group. This revealed that caregivers of HR-ND infants showed marginally greater linear growth in their responses to stationary behaviors than the caregivers of HR-ASD infants ($p = 0.057$). Model estimates did not differ between HR-LD and HR-ASD infants.

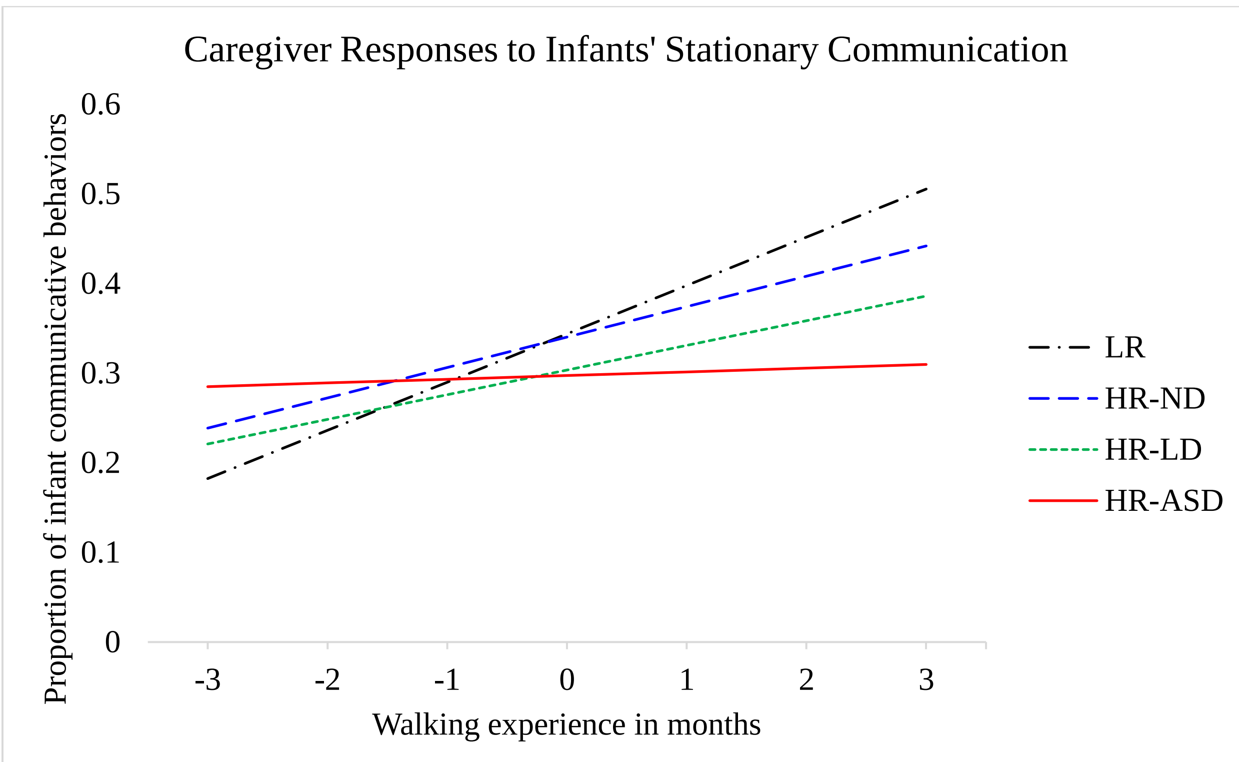

Figure 20 Model Projections of Caregiver Responses to Stationary Communication Over Time

3.5.4 Summary

Across the transition from crawling to walking, infants were increasingly successful in eliciting responses from caregivers. Neurotypically developing infants (both LR and HR) received more contingent verbal responses over time and more responses containing translations (i.e., the object of infants' gesture or vocalization was named). Contrary to our predictions, caregivers of LR and HR-ND infants showed almost identical trajectories of responses to their infants' moving and stationary behaviors.

Notably, caregivers of HR-LD and HR-ASD infants rarely included translations in their responses, and did not increase in the proportion of translations over time. This may be driven by differences in communication exhibited by the HR-LD and HR-ASD infants, compared to their peers. For example, gestures and vocalizations were less directed (paired with gaze to caregiver) for both HR-LD and HR-ASD infants relative to the LR and HR-ND groups, which may have affected the types of responses they elicited.

Caregivers of HR-ASD infants displayed reduced growth in proportion of their behaviors that elicited verbal responses, and this attenuation appeared to be driven by responses to stationary behaviors. Caregivers of HR-ASD infants responded to an equivalent proportion of moving behaviors as LR caregivers did, but they displayed reduced growth in their responses to stationary behaviors.

4.0 DISCUSSION

This dissertation had two overarching goals: a) to investigate whether walking instigates a developmental cascade, altering the way infants move through their environment, the objects they contact, their social interactions with caregivers, their communication, and the verbal responses caregivers provide to that communication; and b) to identify whether this developmental cascade diverges for HR infants, particularly infants later diagnosed with ASD. This research makes multiple novel contributions to our existing knowledge. Despite evidence that same-aged crawling and walking infants differ across many seemingly-unrelated domains (e.g., Walle & Campos, 2014; Biringen, Emde, Campos & Appelbaum, 2008; Clearfield, 2010), little was known about how these domains change as infants begin walking. Our findings uncovered the *shape of change* in infants' interactions with objects and people as they learned to walk. This is a critical step toward understanding how the development of walking, exploration, and communication are functionally related. Results also illuminated differences in this transition for HR-ASD infants relative to their peers. While neurotypically-developing infants (both LR and HR) experienced dramatic changes in the frequency and content of communication, HR-ASD infants' communication remained largely unchanged. Findings related to each of these goals are discussed in turn below.

4.1 The Transition to Walking in Neurotypical Development

Locomotion changed in predictable ways as infants progressed from “crawler” to “walker” status. Time spent walking surged, while crawling and cruising tapered off. However, this switch was not necessarily discrete. Infants continued to crawl and cruise long after they were capable walkers. Although we did not quantify whether infants traveled greater distances when they started walking, it seems likely. Walking bouts lasted substantially longer than crawling or cruising bouts. At the peak of walking (the final session), LR infants walked for 106 seconds on average. In contrast, crawling and cruising peaked at 35 and 33 seconds respectively. Therefore, it is possible that walking enabled infants to explore more of their surroundings, which is consistent with prior work (e.g., Adolph & Tamis-LeMonda, 2012; Thurman, 2017). Moreover, infants contacted more objects in their environments over time. Past research finds that walkers retrieve far-off objects more often than same-aged crawlers do (Karasik, Adolph, Tamis-LeMonda & Zuckerman, 2012). Here we add that the *variety* of objects with which they interact also expands. This is likely impactful, considering that infant-caregiver interactions are frequently centered around toy play (e.g., Belsky & Most, 1981; Bornstein & Tamis-LeMonda, 1990; Fein, 1981; West & Rheingold, 1978). Finally, as in past work, infants also increasingly carried objects with them as they locomoted (Karasik, Adolph, Tamis-LeMonda & Zuckerman, 2012). Clearly, infants’ object interactions undergo substantial changes during this time.

Across the transition from crawling to walking, infants increasingly approached their caregivers and locomoted away from them. This replicates prior findings that walking is associated with an increase in both “proximity-seeking” and “social distancing” behaviors (e.g., Biringen, Emde, Campos & Appelbaum, 2008; Mahler et al., 1975). Social interactions take on a back-and-forth pattern with walking experience, and infants become more active and autonomous in establishing their proximity to caregivers. Walkers venture out from caregivers to explore spaces and things around them, and then return to engage with them. It is surprising that this pattern has not been given more research attention, as it is consistently observed across studies (Biringen, Emde, Campos & Appelbaum, 2008; Mahler et al., 1975; Karasik, Tamis-LeMonda & Adolph, 2014; Thurman & Corbetta, 2017; Clearfield, 2010) and indicates that walking works to structure the timing of dyadic interactions.

Infant communication changed dramatically during the transition to walking. In particular, gestures quadrupled from the first to final session. Past studies show that infants gesture more often after learning to walk (Clearfield, 2008; Walle, 2016). Our findings go a step further, indicating that walk onset was an inflection point for gesture development. That is, the timing of walk onset coincided with a steep increase in gesture production, as infants increasingly pointed, gave, and showed toys to their caregivers, and reached to request objects. Vocalizations also doubled over this period. This constitutes a clear transformation in the frequency of infant communication. Moreover, two distinct qualitative changes were observed. First, vocalizations and gestures were paired with gaze to caregivers more often over time, reflecting enhanced communicative intent (e.g., Clearfield, 2008). Second, the extent to which communication was moving—i.e., coordinated with locomotion—sharply increased at walk onset. Thus, during the transition from crawling to walking, infant communication became more multimodal and complex.

Increasing complexity in infant communication after walking may account for the observed increase in caregivers' contingent responses over time. As infant communication became more frequent and sophisticated, caregivers reciprocally responded to a greater proportion of infants' communicative behaviors. In addition, their responses were more likely to contain a translation (i.e., they labeled an object the infant was looking to or interacting with). Translation responses may be particularly important for infants' language acquisition. Infants are most likely to learn words when the label is presented while the infant is holding and attending to the referent (e.g., Yu & Smith, 2013).

One surprising finding was that caregiver response rates did *not* differ for moving and stationary communication. In fact, these responses followed strikingly similar trajectories. At the initial visit, caregivers responded to roughly 20% of infants' moving and stationary communication. By the final visit, this increased to 50% for both types. This finding stands in contrast to previous reports indicating that caregivers are more responsive to moving bids (Karasik, Tamis-LeMonda & Adolph, 2014). The discrepancy is likely the result of different coding of infant behaviors. Karasik and colleagues specifically focused on instances when infants showed or approached their caregivers with objects. We coded a broader measure of communication, identifying all gestures and vocalizations produced by infants. In future work, we plan to disentangle whether response rates to moving vs. stationary behaviors vary across different types of infant communicative behaviors.

4.2 Evidence for a Developmental Cascade

The notion that motor achievements unlock opportunities for other types of learning has deep roots in developmental psychology (e.g., Piaget, 1964, Gibson, 1988). Recently, the development of walking has been investigated through this lens. Researchers hypothesize that learning to walk presents infants with new opportunities to explore objects and spaces, initiate social interactions, and produce new forms of communication. This dissertation aimed to measure the shape of change in these domains over the transition from crawling to walking. In this section, I will discuss how these changes not only co-occur, but also may be functionally related to one another via cascading processes.

Esther Thelen noted in 2000 that, “movement helps children sample the world more completely” (p. 394). This surely applies to the onset of walking. Walking enables infants to move more quickly and cover much more ground than crawling, expanding infants’ “sampling” of the visual, spatial, and social information available in their environment. Current findings support this association between locomotion and exploration. As walking increased, so too did locomotion to distal objects, as did the variety of objects that infants played with. This does not necessarily mean that walking is a goal-directed means to an end. In fact, infants only occasionally spot a far-away object and then make a clear path to obtain it (Cole, Robinson & Adolph, 2016). Rather, infants seem to move without a specific destination in mind, foraging for interesting stimuli along the way. As infants travel greater distances, they make more discoveries, interacting with a greater variety of objects.

In turn, enhanced object interactions may have a cascading effect on infants’ play and language experiences. Infant-caregiver interactions are frequently structured around toy play (e.g., West & Rheingold, 1978; Belsky & Most, 1981; Bornstein & Lamb, 1992; Fein, 1981). If access to a wider variety of objects increases with walking, so too might the variety of *play forms.* For example, blocks afford counting and stacking, baby dolls afford symbolic play (like pretending to put baby to bed, or feed baby), strollers and carts afford gross-motor movements, and books afford rich literacy-relevant experiences like turning pages and telling stories. Interaction with a greater variety of these objects could engender more diverse play and learning experiences.

Increased object interactions may have a cascading effect on infants' language experiences. Caregivers are sensitive responders: they "follow in" and talk about the things their infants play with (West & Iverson, 2017; Tamis-LeMonda, Kuchirko & Suh, 2018). If walking enables infants to play with more different objects, it could elicit a greater variety of language input from caregivers. Consequently, more and more varied language input likely impacts language learning (e.g., Hoff & Naigles, 2002; Huttenlocher, Haight, Bryk, Seltzer & Lyons, 1991).

Our findings also suggest that walking coincides with new forms of communication. Specifically, there was a significant inflection in *moving* communication (i.e., communication coupled with locomotion) when infants began to walk. Although caregivers' overall response rates did not differ for moving and stationary communication, there is reason to believe that the *content* of their responses could differ. A study by Karasik and colleagues (2014) found that caregivers responded differently to infants' moving vs. stationary bids. They were more likely to provide actions directives (e.g., "stack it", "go give it to Daddy") to moving bids, whereas stationary bids were more likely to receive referential (e.g., "that's a spoon") and affirmation (e.g., "thank you", "good") responses. These different response types could in turn have a reciprocal effect on infant locomotion; e.g., caregivers' action directives may prompt infant actions. In future work, we plan to further investigate whether these changes in communication and exploration may account for changes in infants' language ability.

The fact that so many changes occurred during the transition to walking supports the notion of developmental cascades. That is, that a change in one domain can reverberate across other domains. For developmental researchers, the task of explicating these cascades is important, but difficult. Every achievement in infancy is multiply determined by a constellation of factors—to start: infants' other developing skills (which encompasses a huge spread, with skills as disparate as affordance-perception and theory of mind), interactions with the people, places, and things around them, epigenetic factors, and macro-level influences like culture (e.g., how infants are fed, dressed and cradled), family structure, geography, and even weather/climate. Despite the difficulty of the task, it is important to uncover and connect these cascading processes for multiple reasons. First, deviations in early-emerging skills can have far-reaching consequences. For example, infant walking predicts later vocabulary size, language pragmatics (e.g., the initiation of conversation, coherence, and rapport), and spatial processing (Walle & Campos, 2014; He, Walle & Campos, 2016; Oudgenoeg-Paz, Leseman & Volman, 2015; Logan et al., 2016). Second, doing so informs our understanding of *how* development unfolds. Historically, researchers have measured processes of development within the silos of their own expertise. The present study underscores the need to collaborate across these areas to form a more complete, comprehensive understanding of development.

4.3 The Transition to Walking in Autism Spectrum Disorder

According to most recent estimates, 1 in 40 children in the United States has an ASD (Kogan et al., 2018; Xu, Strathearn, Liu & Bao, 2018). There is a clear need for enhanced understanding of infant development in ASD to inform early intervention services and best serve affected infants and children. Current literature on infants with ASD has overwhelmingly focused on either social communicative or motor development—revealing disruptions in both domains—but far less is known about how these domains interrelate in ASD. The present study examined the concurrent development of independent walking, object interactions, and communication behaviors—and how infants integrated these behaviors—in a sample of HR infants. We observed whether HR-ASD infants displayed different developmental trajectories than their LR and HR peers.

Past research has found evidence that walking develops later and is less proficient in ASD compared to neurotypical development. However, our results uncovered very few differences in the progression of locomotor development leading up to and following walk onset (although there were differences in crawling prior to walk onset). In particular, trajectories of independent walking were similar for HR-ASD infants and their LR and HR peers. There are at least two potential reasons why we did not replicate past findings of atypical walking in ASD. First, past studies have conducted comparisons based on infant age. We employed a milestone-based design, examining whether the progression of locomotor development differed *during the transition* from crawling to walking. It may be the case that walking is delayed in ASD (our data trended in this direction), but that it follows a typical pattern of development. It also possible that our measures of locomotion were not sensitive enough to capture differences. Our duration measure does not provide information regarding infants' steps, speed, stability, gait patterns, or falls. Future work should use more detailed micro-coding and footfall data to capture differences in the quality of walking in HR-ASD infants.

During the transition to walking, HR-ASD infants approached and carried objects more frequently each month, showing the same pattern as their peers. However, unlike their peers, HR-ASD infants did *not* show an increase in the variety of objects with which they interacted over time. Relatively few studies have examined early object interactions in infants with ASD, and the majority of these focus on social aspects such as symbolic and pretend play with objects. For this reason, it is not clear why infants with ASD showed this attenuated growth. These results are consistent with a study by Rowland and Schweigert (2009), which used the *Hands On Learning* instrument (Rowland & Schweigert, 2003)—a parent/teacher report survey of infants' actions with objects—to measure the development of object interactions in 2- to 5-year old children with ASD. Results revealed that the development of object interactions (e.g., accessing objects, simple actions with objects) were delayed in ASD compared to neurotypical development. However, research on this topic is very sparse, and more work is needed to probe whether this difference is robust.

Notably, HR-ASD infants experienced attenuated growth in *every* communication variable compared to LR and HR-ND peers. This is consistent with findings that communication is atypical among infants with ASD (e.g., Jones et al., 2014). The results reported here add to this work, showing that communication frequency was largely unchanged following the onset of walking for HR-ASD infants. In contrast to LR and HR-ND infants, there was no inflection in gesture development at walk onset for HR-ASD infants. Moreover, HR-ASD infants produced far fewer moving gestures and vocalizations than their neurotypical peers, showing no inflection at walk onset. At the final session, HR-ASD infants produced four times fewer moving communicative behaviors than the LR and HR-ND groups.

The HR-ASD group's communication also differed from HR-LD group. Overall, HR-ASD infants gestured and vocalized less often than HR-LD peers. However, the largest discrepancies were observed for communication that was directed (paired with eye gaze) and moving (paired with locomotion). Thus, communication was less multimodal for HR-ASD infants than their language-delayed peers. This aligns with growing work indicating that communication is less coordinated in ASD than in neurotypical samples (Parlade & Iverson, 2015; Heymann et al., 2018; Sowden, Clegg, & Perkins, 2013). Coordinated communication (for example, combining gestures and vocalizations into a single communicative act) is an advanced form of early communication. One such study by Parladé & Iverson (2015) measured gesture-vocalization coordination in HR infants from 8 to 24 months. Both HR-LD and HR-ASD groups produced few coordinations initially. By 12 months, HR-LD began to coordinate behaviors, increasing at a rate comparable to LR peers. In contrast, coordinations remained low for HR-ASD infants—they were almost unchanged across the period. Our findings extend this work, showing that infants with ASD not only combine communicative behaviors (like gestures and vocalizations) less frequently, they also pair them with other types of behavior (locomotion) less often. The coordinated quality of communicative behaviors—not just base-rates alone—may be useful in distinguishing infants with ASD from peers with non-ASD developmental delay.

The communication behaviors of HR-ASD infants also received fewer contingent verbal responses from caregivers over time. This pattern appears to be driven by responses to HR-ASD infants' stationary communicative behaviors. Over time, caregivers of HR-ASD infants increasingly responded to infants' moving behaviors. But they did not show the proportionate increase in their responses to stationary behaviors that was observed among caregivers of LR and other HR infants. It may be that over time, the communicative behaviors of neurotypical infants become more complex and salient to caregivers, regardless of whether they are moving or stationary; this is supported by our finding that communication becomes more socially-directed over time for LR, HR-ND, and HR-LD infants. However, this may not the case for HR-ASD infants, and their stationary behaviors may be more easily overlooked. Because HR-ASD infants both produced fewer communicative behaviors *and* received proportionately fewer responses, it is likely that there are considerable differences in language input that they elicit during this period in development.

Although there is substantial evidence that communication and motor development are both disrupted in infants with ASD, there has been a relative lack of research investigating interrelations across the two domains. The few studies that have investigated links between these domains have taken two approaches: 1) measuring correlations between the timing of motor milestones and later communicative ability (e.g., Kim, 2008; Bedford et al., 2015), or 2) testing whether communicative ability varies as function of infants' "crawler" or "walker" status (e.g., Bradshaw et al., 2018). This is the first study to examine how HR-ASD infants integrate locomotion and communication behaviors spontaneously, and further, how this ability evolves longitudinally as they learn to walk.

This new knowledge may inform early intervention strategies. Many early interventions are effective in improving outcomes of toddlers with ASD (e.g., Dawson et al., 2010). Currently, speech therapy, physical therapy, and occupational therapy are popular forms of intervention, and for good reason—they are among the most effective strategies (Autism Science Foundation, www.autismsciencefoundation.org). Speech therapy is administered by a speech language pathologist (with the help of parents and teachers) to improve infant communication (e.g., enhanced clarity of speech, gestures and body language, and use of speech-generating devices). Physical therapists focus on motor abilities, including coordination, balance, and specific skills like walking. Occupational therapists also target motor abilities as a means of promoting every-day skills (e.g., strengthening fine motor ability to improve toddlers' use of utensils). Although toddlers sometimes receive multiple interventions simultaneously, intervention activities are carried out separately. This study—among others (e.g., Bhat, Lobo & Galloway, 2011)—suggests interventions could be strengthened by *integrating* these activities into a more holistic, comprehensive approach. For instance, an infant with difficulty walking may benefit from efforts to enhance their strength and balance walking, and from simultaneous efforts to coordinate this enhanced walking behavior into social interactions and exploration; i.e., by exploring far-off toys, carrying objects to share, or approaching distal caregivers to interact. By integrating locomotor behavior into every-day play activities, infants have increased opportunity to practice and refine their locomotor skill, and parallel improvements in the quality and variety of their exploration and play. Thus, a comprehensive approach has the potential to positively impact multiple developmental domains in concert.

4.4 General Conclusions, Limitations, and Future Directions

This study had many notable strengths: it employed a dense longitudinal design, sampling data over a period of seven months, which allowed us to establish baseline growth in each variable and thus empirically test whether walk onset marked an inflection point the developmental trajectory. Further, we included a large sample of HR infants, which enabled us to determine whether growth trajectories differed among three outcome groups—infants who developed neurotypically, infants who exhibited delayed language, and infants who were later diagnosed with ASD. However, it is important to acknowledge some limitations.

First, this study was observational. We were not able to establish causal or directional links among variables of interest—we were only able to measure trajectories of their simultaneous development. The relations among communication, exploration, and walking are likely bidirectional and multiply determined. Infants' desire to explore and socially engage may drive their walking behavior and development. When infants do attain motor milestones, new opportunities for communication and exploration are unlocked. Thus, the associations between these domains are dynamic and transactional. And there are assuredly other variables that influence both walking and communication behaviors. For example, features of infants' temperament are related to language development (e.g., Slomkowski, Nelson, Dunn & Plomin, 1992), as well the timing of their motor milestone attainment (Biringen et al., 2008). Future studies with experimental designs are needed to tease apart potential causal relations.

Additionally, we sampled 10 minutes of behavior at each session. This prevented us from capturing behaviors that have low base-rates. In particular, we were unable to capture sufficient levels of word production. At this point in development (around the end of the first year) infants are just beginning to produce words, and they do so infrequently. Had we observed longer windows of time, it is possible we would have captured more utterances containing words.

Finally, the naturalistic observations were not recorded with the intention of capturing detailed information about infant gait. It was not possible to code variables related to the symmetry or speed of infant locomotion. Future work should use fine-grained measures (e.g., kinematic measures; footfall measures) to capture meaningful individual differences in the proficiency of walking.

Together with the larger literature, this dissertation provides support for the hypothesis that walking instigates a developmental cascade, prompting change in infants' social interactions and exploration. These changing experiences shape infants' opportunities for learning and may therefore have ripple effects on the development of higher-level skills, including language. Additionally, it is increasingly evident that the transition to walking unfolds differently for infants with ASD. The transition marks a point in development when the gap in communication between ASD and neurotypical infants widens. Therefore, in addition to examining developmental change as it relates to chronological age, it is crucial to observe changes during motor transitions, which appear to occur on a different timescale for infants with ASD.

Appendix A Correlation Matrix of All Dependent Variables

Table 12 Partial Correlations Among Dependent Variables Controlling for Age

	Crawl	Cruise	Walk	Social Approach	Social Disengage	Object Approach	Object Carrying	Object Variety	Gestures	Vocs	Moving Comm.	Directed Comm.	Responses	Translations	Moving Responses	Stationary Responses
Crawl	—															
Cruise	-.04	—														
Walk	-29***	-.10*	—													
Social Approach	.11**	.06	.05***	—												
Social Disengage	.22***	.05	.47***	.69***	—											
Object Approach	.24***	.09*	.41***	.47***	.53***	—										
Object Carrying	-.06	.12**	.62***	.42***	.41***	.44***	—									
Object Variety	.06	-.04	.12**	.15***	.15***	.42***	.19***	—								
Gestures	-.15**	-.09*	.06	.09*	.03	.09*	.03	-.01	—							
Vocs	-.04	.10*	.22***	.17***	.20***	.17***	.21***	.05	.17***	—						
Moving Comm.	.04	.28***	.60***	.47***	.51***	.45***	.53***	.11*	.14**	.66***	—					
Directed Comm.	-.17***	-.03	.16***	.19***	.14**	.08†	.13**	-.02	.47***	.67***	.42***	—				
Responses	-.14**	-.01	.00	.02	.06	.11*	-.02	.17***	.30***	-.01	-.03	.22***	—			
Translations	-.06	-.06	-.05	-.02	.04	.11**	-.05	.18***	.33***	.01	-.02	.04	.53***	—		
Moving Responses	-.13**	-.02	-.01	.41	-.02	.00	-.06	.04	.14**	-.04	-.06	.13**	.57***	.26***	—	
Stationary Responses	-.14**	-.01	-.05	-.01	.02	.07	-.02	.16***	.30***	.01	-.05	.21***	.92***	.49***	.35***	—

Appendix B Coding Descriptions

B.1 Locomotion

Tier 1.1: Bouts of locomotion

In this tier, we are identified moments when the infant was ‘locomoting’, which could mean crawling, walking, or cruising. Criteria:

- Must consist of at least 2 steps (or crawl cycles)
- the infant must change location (i.e., walking in place does not count)
- Steps must occur within .5 seconds intervals (if the infant paused for more than .5 seconds while locomoting, this was treated as two separate bouts)

This was a duration code:

- Onset: the first frame in which the infants’ leg (or arm in instance of arm-dominant crawl styles) is in motion.
- Offset: the frame in which, during the final step, the leg (or arm) reached the floor.

All subsequent locomotion tiers categorized these bouts along some dimension.

Tier 1.2: Crawl or walk

If the infant was an upright posture, coded ‘walk’. If the infant was on the floor (typically on all fours), coded ‘crawl’.

Tier 1.3: Social partner at destination?

We coded whether an infant approached a social partner. If the infant was *not near* caregiver (or team leader) at the start, and then locomoted to them, coded ‘yes’. If caregiver followed the infant to the destination (e.g., in instances of “hitching”) coded as “follows”. All other instances were coded as ‘no’.

Tier 1.4: Disengaged from social partner?

We coded whether or not the infant walked or crawled away from a caregiver or team leader. This was the inverse of Tier 3. Coded ‘yes’ if infant was near caregiver (or TL) initially, and then locomoted away from them.

Tier 1.5: Carried an object?

We coded whether—during the bout of locomotion—the infant carried an object. We coded 'yes' if this occurred at any point during the bout. During crawling bouts, this often looked like they're pushing the object with them as they crawl. We coded 'yes' in these instances.

Tier 1.6: Object at destination?

We coded whether the infant approached an object during each bout. If infants' locomotion bout ended with them immediately touching/grabbing a toy, code as 'yes'.

Tier 1.7: Using support?

Did infants have an external source of support while locomoting? This was always 'no' for crawling. For walking, this was coded as 'yes' if infant cruised along furniture, used a push walker toy, or if a parent held their hand.

B.2 Gesture

Tier 2.1: Gestures

In this tier, we identified Deictic Gestures:

- Give: infant handed an object to a social partner.
- Show: infant held up an object to show a social partner
- Reach: infant reached for an out-of-reach object
- Index Finger Point: infant pointed to an object with an isolated index finger
- Index Finger Touch: infant touched an object with an isolated index finger

This was not a duration code, so duration was set to around 1 second (but variations in duration are not meaningful—this is a point-event code). All subsequent Tiers categorized some dimension of the identified gestures.

Tier 2.2: Moving or Stationary?

If the gesture occurred during or two seconds after a bout of locomotion, it was coded as "Moving". Otherwise, it was coded as "Stationary".

Tier 2.3: Directed or Undirected?

If during the gesture, the infant looked at the social partner, it was coded as "directed". Otherwise, it was coded as "undirected".

Tier 2.4: Caregiver verbal response?

Coders watched for 2 seconds following the gesture. If during this time, the caregiver verbally responded, it was coded as "yes". Otherwise, it was coded as "no".

Tier 2.5: Response contained a translation?

If "no" was coded on the previous tier, this tier was left blank. If the caregiver did verbally respond, coders further specified whether the response contained a translation ("yes" or "no"). A translation was defined as: a label corresponding to the referent of the infant's gesture. For example, if the infant pointed at a dog and the response contained "dog", this was coded as a translation. "Label" was inclusive. For instance, the pet's name, "animal", "pet", "paws" etc, could count. Essentially, any concrete noun that could be used to refer to that object or a part of that object.

B.3 Vocalization

Tier 3.1: Vocalizations

In this tier, we identified vocalizations (abbreviated as vocs):

- Non-word vocs: sounds produced by the infant. This did NOT include vegetative sounds like sneezing, coughing, breathing, or affective sounds like laughing, fussing, and crying.
- Vocs with words: vocs that contained either an English word, or a speech sound consistently used to refer to an object with half of the morphemes (e.g. “bah-bah” to refer to a bottle).

As in gestures, this was not a duration code, so the length was standardized at 1 second. Any variation in duration were not meaningful, codes are point-events. All subsequent Tiers are categorized some dimension of these identified vocs.

Tier 3.2: Moving or Stationary?

If the voc occurred during or 2 seconds after a bout of locomotion, this was coded as “Moving”. Otherwise, it was coded as “Stationary”.

Tier 3.3: Object-directed, Parent-directed, or Undirected?

If during the voc, the infant looked at the social partner, it was coded as “parent-directed”. If during the voc, the infant looked at an object, it was coded as “object-directed”. Otherwise, it was coded as “undirected”.

Tier 3.4: Caregiver verbal response?

Coders watched for 2 seconds following the voc. If during this time, the caregiver verbally responded, it was coded as “yes”. Otherwise, it was coded as “no”.

Tier 3.5: Response contained a translation?

If “no” was coded on the previous tier, this tier was left blank. If the caregiver did verbally respond, coders further specified whether the response contained a translation (“yes” or “no”). A translation was defined as: a label corresponding to object the infant was looking at.

For example, if the infant was looking at a dog and the response contained “dog”, this was coded as a translation. “Label” was inclusive. For instance, the pet’s name, “animal”, “pet”, “paws” etc, could count. Essentially, any concrete noun that could be used to refer to that object or a part of that object.

B.4 Object Exploration

Tier 4.1: Infant touched object with hands

In this tier, we identified moments when the infant touched an object. Either the whole hand or part of the hand was in contact with object. In order to be included, contact with the object last at least 0.5 seconds (i.e. fleeting instances where the hand or finger graze an object were not counted). This was NOT a duration code—each touch is a point event.

Tier 4.2: Name of object

Coders annotated what the object was (e.g. “teddy bear”).

Tier 4.3: Total number of objects

Coders counted the total number of unique objects the infant contacted.

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