Coordinated Communication and Walking in Infants at Heightened Risk for Autism Spectrum Disorder

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Autism spectrum disorder (ASD) is characterized by communication difficulties during infancy (Jones et al., 2014). Additionally, infants with ASD learn to walk later than neurotypical infants (West, 2018). Overwhelmingly, studies focus on either communication or motor behavior, but infant development does not behave so independently. Motor delays may have cascading adverse effects on communication. This study bridges motor and communication research, investigating how learning to walk—a major motor achievement—affects how neurotypical infants and those with ASD gesture. One hundred and sixteen infants were seen in their homes on a monthly basis from 5-18 months of age. Twenty-five infants had no family history of ASD. Ninety-one infants had an older sibling with an ASD diagnosis and were assessed by a clinician at 36 months. Based on clinical best estimates, infants were assigned to one of three outcome categories: no diagnosis, language delay, or ASD diagnosis. This study focused on data from 7 monthly sessions, which were anchored by infants' walk onset. At each session, we coded the frequency of gestures and the extent to which they were paired with vocalizations or social gaze during 10 minutes of naturalistic play. Results revealed that infants who developed typically—regardless of genetic risk for ASD—increasingly coordinated gestures with vocalizations and gaze after they started walking. Conversely, infants later diagnosed with ASD produced fewer gestures overall and did *not* increase their coordinated gestures after they began walking. Findings may inform early intervention strategies for very young children with ASD. Specifically,

comprehensive clinical strategies should integrate motor-based approaches (e.g., physical therapy) with communication-focused approaches (e.g., speech-language therapy) to maximize client progress.

Table of Contents

List of Tables

List of Figures

Preface

This research was supported by grants from Autism Speaks and the National Institutes of Health (R01 HD41607 and R01 HD54979) to Jana M. Iverson.

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1.0 INTRODUCTION

Infants with autism spectrum disorder (ASD) experience delays and difficulties in communication. They babble, gesture, and talk later and less often than do typically developing infants (e.g., Jones et al., 2014). Notably, their communication is also less *coordinated* (e.g., Heymann et al., 2018; Parladé & Iverson, 2015; Sowden et al., 2013). Coordinated communication (i.e., combining multiple behaviors such as gestures and vocalizations into a single communicative act) is an important skill and is a hallmark of mature speakers.

Infants with ASD also experience delays in motor development, including delayed motor milestones (e.g., sitting, crawling, walking; West, 2018). Additionally, infants with ASD use new motor skills less often than neurotypical infants (e.g., spending less time in unsupported sitting; Leezenbaum & Iverson, 2019). These motor disruptions could constrain communication development. Despite the now widely reported delays in motor and communicative development, very little research has examined how these domains interrelate in infants eventually diagnosed with ASD.

Research on neurotypical infants has shown that new motor skills set the stage for communication advances (He et al., 2015; Oudgenoeg-Paz et al., 2012; Walle, 2016; Walle & Campos, 2014; West, 2019; West et al., 2017). For instance, infants integrate locomotion with gestures, and show increased growth in the production of language, gestures, and vocalizations when they begin to walk (e.g., Clearfield, 2008, 2011; Karasik et al., 2011; Walle & Campos, 2014). To illustrate, a walking baby may wander around the house, select an interesting toy, and carry it over to a parent, holding it up to show it. The parent may then respond in turn (e.g., "Is this your car?"). While there is evidence that isolated communicative behaviors are increasing as infants learn to walk, we do not know whether they are also increasing their integration of these behaviors (e.g., combining a gesture with a vocalization). Therefore, there were two central questions guiding this study. First, how does coordinated communication change as neurotypical infants transition from crawling to walking? Second, how does coordinated communication change in infants at heightened risk for ASD who exhibit diverse developmental outcomes (e.g., ASD, language delay, neurotypical development)? Do they experience a different trajectory compared to infants with no such risk?

1.1 Coordinated Communication in Neurotypical Development

Before infants start to talk, they communicate with their caregivers through pre-linguistic behaviors such as gestures, vocalizations, and gaze—sometimes coordinating these behaviors together. Indeed, instances of coordinated communicative behaviors can be seen in neurotypical infants as young as 3 months old, as infants begin to pair behaviors like smiles with their vocalizations (e.g., Yale et al., 2003; Yale et al., 1999). By 2 years of age, bouts of coordinated communication are both temporally aligned and semantically related (e.g., Butcher & Goldin-Meadow, 2000; Wetherby et al., 1988). That is, two communicative behaviors, such as a gesture and a vocalization, apply to the same referent (e.g., infant points at bottle while simultaneously saying [baba]).

Coordinated communication is a precursor to more advanced communicative behaviors and a hallmark of mature speakers (e.g., Crais et al., 2009). Research shows that production of gestures coordinated with other communicative behaviors (gaze, vocalization) is predictive of later language development (e.g, Donnellan et al., 2020; Parladé et al., 2009; Rowe & Goldin-Meadow, 2009). In fact, infants' combination of vocalizations and gestures both precedes and predicts early language advances (Iverson & Goldin-Meadow, 2005).

Coordinated communication is also likely to be salient to caregivers, acting as an effective tool for fostering social interactions (e.g., Crais et al., 2009; Donnellan et al., 2020; Goldin-Meadow et al., 2007; Martinsen & Smith, 1989). When infants gesture with a vocalization, caregivers are highly likely to respond (e.g., "Is that your bear?", as an infant points to the teddy bear and vocalizes; Goldin-Meadow et al., 2007; Leezenbaum et al., 2014), and these responses appear to support language learning. For instance, Donnellan and colleagues (2020) found that gestures and vocalizations coordinated with eye gaze elicited more contingent responses from caregivers compared to behaviors without gaze. Importantly, gaze-coordinated vocalizations that received contingent responses were most predictive of infants' later language skills, compared to isolated vocalizations and/or ones that did not receive a response (Donnellan et al., 2020). Thus, coordinated communication is not only an important communication milestone in and of itself, it is also influential in eliciting language input from caregivers.

1.2 Communication and Walking in Neurotypical Development

For neurotypical infants, learning to walk is accompanied by accelerated growth in language, regardless of infant age (e.g., Walle, 2016; Walle & Campos, 2014; West, 2019; West et al., 2017). One explanation for this additional growth in language is that social opportunities increase substantially when infants begin to walk. Walking enables infants not only to have an elevated vantage point due to their upright stance, but also to travel much farther. Adolph et al. (2012) found that even novice walkers traveled three times farther than expert crawlers. Newly walking infants have a greater ability to explore not only their environments but also the people in it. As West (2019) concluded, walking instigates a developmental cascade that affects both social interactions and exploration.

A growing body of literature has made it clear that prelinguistic communication also changes as infants begin to walk (e.g., Clearfield, 2008, 2011; Karasik et al., 2011; Walle, 2016). For example, novice walkers gesture more than age-matched crawlers (Clearfield, 2008, 2011). Although these studies have documented an increase in overall frequency of communication after walk onset, little is known about how infants integrate *multiple* communicative behaviors (e.g., gestures with vocalizations or eye gaze) during this transition. There is reason to believe that communication may become more coordinated with walking. For example, in a cross-sectional study, Clearfield (2010) found that walking infants paired gestures with eye gaze more often than same-age crawling infants. However, to date no longitudinal study has examined whether coordination changes with walking development.

1.3 Communication and Walking in ASD

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). Children are generally not diagnosed with ASD until 40 months of age (Christensen et al., 2016), which makes it difficult to study its development in infancy. To study infants prior to diagnosis, researchers recruit infants who have an older sibling with ASD. These infant siblings are themselves at heightened biological risk (Heightened Risk; HR) for ASD. The ASD recurrence rate for HR infants is 18.7% (e.g., Ozonoff et al., 2011), which is substantially higher than the 1.69% prevalence rate in the general population (Centers for Disease Control and Prevention [CDC], 2019). In addition, HR infants who do *not* receive an ASD diagnosis are also at heightened risk for language delay (Marrus et al., 2018). Recruiting HR infants allows us to follow them prospectively until an age when reliable diagnosis and then compare data from infants who develop ASD to those who are neurotypical or have a language delay. Comparing the development of infants with ASD to that of infants with language delay is especially useful for identifying unique markers and thus differentially diagnosing ASD.

Research shows that older children with ASD display differences in walking gait (e.g., Accardo & Barrow, 2015; Eggleston et al., 2017; Esposito & Venuti, 2008; Esposito et al., 2011). Prospective HR infant studies allow us to measure motor development in ASD throughout infancy, and more specifically during crucial transitions such as the onset of walking. Infants who develop ASD display delayed and less proficient motor milestones, including a later walk onset compared to neurotypical peers (e.g., Bhat et al., 2010; Garrido et al., 2017; West, 2018, 2019). As previously discussed, walk onset is a point of inflection for language growth in neurotypical infants (e.g., Clearfield, 2008, 2011; Karasik et al., 2011; Walle & Campos, 2014). The period of transition from crawling to walking may therefore be a time when infants with ASD begin to fall further behind their peers in communicative development.

As described above, HR infants with ASD experience broad delays and difficulties in communication (e.g., Jones et al., 2014): they babble, gesture, and talk later and less frequently than do their neurotypical peers (e.g., Jones et al., 2014). Iverson and colleagues (2018) found that infants with ASD produce significantly fewer gestures than neurotypical infants, with group differences apparent as early as 9 months of age. Similarly, Choi and colleagues (2019) reported that the infants with ASD in their study produced significantly fewer gestures than their neurotypical peers by 12 months of age.

With regard to coordinated communication, previous research has reported that relative to neurotypical peers, older children with ASD display difficulties integrating multiple communicative behaviors into a single message (e.g., Shumway & Wetherby, 2009; Stone et al., 1997). There is some evidence that these differences emerge around one year of age. For example, Parladé and Iverson (2015) demonstrated that, compared to neurotypical infants, HR infants eventually diagnosed with ASD produced significantly fewer gestures coordinated with vocalizations as early as 12 months of age. Similarly, Heymann and colleagues (2018) found that 14-month-old HR infants who later received an ASD diagnosis were less likely to coordinate vocalizations and joint attention behaviors (e.g., gestures and gaze) than their neurotypical peers. Further, Choi and colleagues (2019) reported that at 12 months of age, HR infants who did not receive an ASD diagnosis produced a significantly larger number of gesture-vocalization combinations than HR infants who did receive an ASD diagnosis.

Taken together, the existing evidence strongly suggests that by the end of the first year, a time when neurotypical infants are making rapid gains in communication, infants with ASD appear to be falling behind their peers, particularly in the development of coordinated communication. Moreover, there is reason to believe that communication develops in a broader context—one that includes motor development—and infants with ASD experience delays and differences in the development of fundamental early motor skills. No studies to date have investigated potential changes in coordinated communication over the transition from crawling to walking—in ASD *or* neurotypical development. This study was designed to address this gap.

1.4 Study Aims and Hypotheses

Studies of HR infants have largely focused on either language development *or* motor development. Few studies to date have attempted to study interrelations among these delays. West (2019) found that for infants with ASD, walk onset does *not* mark a point of inflection in gesture development as it does for neurotypical infants. The present study builds on this finding by examining change in the production of gestures coordinated with other communicative behaviors (i.e., gestures paired with vocalizations or eye gaze) longitudinally during the transition from crawling to walking. The study had two primary aims.

The first aim was to examine how coordinated communication changes as infants transition from crawling to walking. Based on previous cross-sectional findings (e.g., Clearfield, 2008, 2011; Karasik et al., 2011), I hypothesized that the frequency of coordinated communication would increase among neurotypical infants when they began walking.

The second was to determine whether the development of coordinated communication across this transition period varied among HR infants with different developmental outcomes, in particular, among infants later diagnosed with ASD. In light of prior research on communication development in ASD (e.g., Choi et al., 2019; Heymann et al., 2018; Jones et al., 2014; Parladé and Iverson, 2015; West, 2019), I expected that infants with ASD would show reduced growth in both coordinated and uncoordinated gestures following walk onset. Specifically, over walk onset, I expected that infants with ASD would not increase their production of gestures coordinated with vocalizations or gaze, nor gestures produced without vocalizations or gaze, to the same degree that neurotypical infants did.

2.0 METHODS

The present study is an extension of a previous investigation of communicative and social development during the transition from crawling to walking in infants with low versus heightened risk for ASD. The methods described below are adapted from the larger project as data collection and elements of coding schemes are shared between the two studies. For additional details on the methods employed in the original study, see West (2019).

2.1 Participants

The present study included 116 infants in two main groups: low risk (LR) and heightened risk (HR). The LR group was comprised of 25 infants (15 female) with no first-degree relatives with ASD. Of these 25 infants, 16 had at least one older, typically developing sibling and 9 were first-born. The HR group consisted of 91 infants (43 female) who had at least one full biological sibling diagnosed with ASD. The HR infants' older sibling was administered the Autism Diagnostic Observation Schedule-Generic (ADOS-G; Lord et al., 2000) by a trained, research-reliable clinician to confirm ASD diagnosis. If the older sibling met the threshold score for either Autistic Disorder (AD) or ASD, the infant was enrolled.

All 116 infants were from full-term, uncomplicated pregnancies and monolingual English-speaking households. Demographic characteristics, displayed in Table 1, did not differ significantly across groups—apart from parental age. HR infants had older mothers, $F (1, 114) = 5.59$, $p = 0.02$, and fathers, $F (1, 114) = 9.72$, $p = 0.02$, compared with LR infants. Increased parental age is common in studies of ASD (e.g., Durkin et al., 2008). Of the 116 infants enrolled in the study, 105 (81 HR, 24 LR) were Caucasian, 10 (HR) were Hispanic, and one LR infant was Asian American. Parents' education levels were similar across groups. The majority had earned either a college degree or completed some college. Nakao-Treas occupational prestige scores (Nakao & Treas, 1994) were calculated in order to provide an index of socioeconomic status. Since a majority of the mothers in both groups stayed at home with their infant, fathers' occupations were used to calculate scores. Paternal occupational prestige scores did not differ significantly between the two cohorts.

Table 1. Demographic Information for HR and LR 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	(4.95)	34.19	(4.04)
Mean age for Fathers (sd)	33.16	(4.47)	36.68	(5.13)
Mean Parent Education[a] (sd)	1.38	(0.51)	1.22	(0.50)
Mean Paternal Occupation Prestige[b] (sd)	55.21	(14.41)	55.37	(15.30)

[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 2 LR and 7 HR fathers.

2.2 Procedure

Both groups of infants were visited in their homes for approximately 45 minutes and videotaped during both unstructured and semi-structured play. The only difference in procedure between the HR and LR groups was in regard to the observation schedule. While HR infants were visited monthly between the ages of 5 and 14 months, LR infants were seen biweekly between the ages of 2 and 19 months. Additionally, HR infants had follow-up visits at 18, 24, and 36 months.

This study focused on a window of seven visits anchored by infants' walk onset, regardless of chronological age. The 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, with the final crawl-only visit (i.e., the visit just prior to infants' walk onset) serving as the window's mid-point. 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 were designated as walk onset). This was to ensure that risk status differences were not a result of different observation schedules.

All parents were given a calendar to help them track their infants' motor milestones, and walk onset was established through parent report. Walk onset was defined as the first visit in which the infant took three consecutive, alternating, independent steps with no support from a caregiver and/or furniture. 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 walk by the end of the monthly visits (14 months), parents were contacted by phone monthly thereafter to establish walk onset. This occurred for 14 HR infants (6 ND, 4 LD, and 4 ASD), who therefore contributed only partial data to the analyses. Given that these missing data did not occur at random, we ran additional models with these infants excluded. Because the exclusion of these infants did not alter significant findings, the results reported include data from the full sample.

2.3 Outcome Measures

HR infants' outcome group status was determined through the collection of measures at three follow-up visits (18, 24, and 36 months). These measures are detailed below, along with a description of how scores were used in determining HR infants' placement in the outcome groups.

2.3.1 MacArthur-Bates Communicative Development Inventory

At 18, 24, and 36 months, the HR infants' primary caregiver completed the MacArthur-Bates Communicative Developmental Inventory (CDI; Fenson et al., 2002). Extensive research has shown that the CDI is both reliable and valid in measuring language ability and detects patterns of atypical language development across a range of samples—most notably ASD (e.g., Charman et al., 2003; Dale et al., 1989; Fenson et al., 1994; Luyster et al., 2007; Miller et al., 1995; Mitchell et al., 2006; Thal et al., 1999).

Based on infants' language ability, caregivers were given either the Words and Gestures form of the CDI (CDI-I) or the Words and Sentences form (CDI-II) at infants' 18-month visits. Caregivers were given the CDI-I if they indicated that the child had very few words. The CDI-I is a 396-item vocabulary checklist which has parents report on both receptive language (i.e., words that their infant only understands) and expressive language (i.e., words that their infant both understands *and says*), as well as gestures and actions. Caregivers were given the CDI-II (detailed below) at 18 months if the infant was producing words frequently or combining words.

All caregivers completed the CDI-II at infants' 24-month visit. The CDI-II is a 680-item vocabulary checklist that asks about expressive language as well as infants' morphology and syntax.

At the final follow-up visit (36 months), caregivers were given the CDI-III to complete. The CDI-III, appropriate for infants aged 30-37 months, is a 100-item checklist in which caregivers report on infants' expressive language as well as their grammar, semantics, and pragmatics.

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 that is administered by a trained experimenter. It consists of five subscales (Fine Motor, Visual Reception, Expressive Language, Receptive Language, and Gross Motor) and provides an index of infants' general cognitive functioning from birth through 68 months. It has strong internal consistency, ranging from 0.83 to 0.95.

2.4 Outcome Classification

HR infants were classified into one of the following three outcome groups, HR-ASD, HR-LD (language delay), and HR-ND (no diagnosis), based on 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-5 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 10^{th} percentile at more than one time point between 18 and 36 months.
2. Standardized scores on the CDI-III at or below the 10^{th} 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 et al., 1997; Heilmann et al., 2005; Robertson & Weismer, 1999; Weismer & Evans, 2002) as well as HR infants (Iverson et al., 2018; Ozonoff et al., 2010; Parladé & 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. There was no indication that LR infants developed atypically. MSEL scores for the three HR outcome groups at 36 months are presented in Table 2.

Table 2. 36-Month MSEL T-Scores for Each HR Outcome Group

	HR-ND			HR-LD			HR-ASD		
	M	*SD*	*Range*	*M*	*SD*	*Range*	*M*	*SD*	*Range*
Visual Reception	58.52	12.675	24-80	52.00	14.675	20-73	30.18	12.392	20-60
Fine Motor	49.18	12.852	26-78	43.15	13.004	20-67	25.62	7.124	20-38
Receptive Language	53.48	8.723	35-40	44.69	8.162	30-64	27.82	10.018	20-44
Expressive Language	57.62	8.204	40-78	48.08	9.744	20-63	30.54	10.389	20-52

2.5 Coding

A 10-minute segment of naturalistic interaction between caregiver and infant was coded for each visit. During the 10 minutes, the caregiver and infant were interacting naturally (i.e., they were told to do what they normally do) and the infant was *not* in a highchair. For the majority of the sessions, this 10-minute segment was continuous (663 of 674 sessions; 98.8% of LR sessions; 98.2% of HR sessions). The remaining 11 sessions involved the infant being sporadically placed in a highchair, and thus 10 continuous minutes could not be obtained (1.2% of LR sessions; 1.8% of HR sessions). These 11 sessions were therefore broken into two pieces (e.g., from 2:00-7:00 and 10:00-15:00 minutes), thereby still allowing a full 10 minutes to be utilized. All 674 sessions were coded for 10 minutes (i.e., no infant had a shorter segment). Coding was completed by one primary and five secondary coders in version 4.8 of Elan for Windows (http://tla.mpi.nl/tools/tla-tools/elan; Lausberg & Sloetjes, 2009). All coders were naïve to infants' risk status and outcome classification.

2.5.1 Infant Communication

Coding manuals are presented in Appendix A. All spontaneous, deictic gestures that the infant produced were coded. *Spontaneous* implied that the gesture was not elicited by a caregiver (Iverson & Goldin-Meadow, 2005). For example, if the caregiver said to the infant "Where's your bottle?" and the infant pointed to a bottle, the pointing gesture was considered elicited (i.e., *not* spontaneous) and thus was not coded. Deictic gestures were chosen for this study because they occur frequently and are not part of ritualized routines (e.g., waving bye-bye, clapping; e.g., Bates et al., 1975). Deictic gestures included:

1. Gives: infant handed an object to a social partner
2. Shows: infant held up an object to show a social partner
3. Reaches: infant reached with an open hand to request a distal object
4. Index finger points: infant pointed to a distal target with an isolated finger (i.e., the finger did not make contact with the target)
5. Index finger touches: infant touched an object with an isolated index finger

We also determined whether or not gestures co-occurred with eye gaze and/or vocalizations. Consistent with Clearfield (2011), a gesture was coded as *directed* if it temporally co-occurred with eye gaze towards a social partner. Vocalizations were separately identified as part of the larger study (see West, 2019 for further detail). Vocalizations were defined as any vowel, consonant, or vowel-consonant combination that the infant produced. Vegetative sounds (e.g., coughing, sneezing, breathing) and affective sounds (e.g., laughing, fussing, crying) were not coded. To be considered as co-occurring, a vocalization and gesture had to either overlap in time or occur within 0.5 seconds of one another.

2.5.2 Reliability

Secondary coders double-coded videos with the primary coder during training. Once they met the threshold scores (κ = 0.80) on three consecutive videos, reliability was established and secondary coders began working independently. Additionally, coders double-coded 19% of all videos to ensure data quality and prevent coder drift. Any discrepancies while coding were discussed and resolved within the group. Original codes were used to calculate reliability data. Revised codes were used in the final analyses. For identification of gestures, mean percent agreement was 83% (64 – 100%). For categorizing coordination of gestures with eye gaze, Cohen's kappa was κ = 0.92. Cohen's kappa for categorizing coordination of gestures with vocalizations was κ = 0.882.

2.5.3 Data Reduction

Raw data coded at each time point in Elan were extracted and exported into Version 24 of IBM SPSS. 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.

Four primary variables were calculated from the raw data: a) total number of gestures coordinated with vocalization; b) total number of gestures produced without vocalization; c) total number of gestures coordinated with eye gaze; and d) total number of gestures produced without eye gaze.

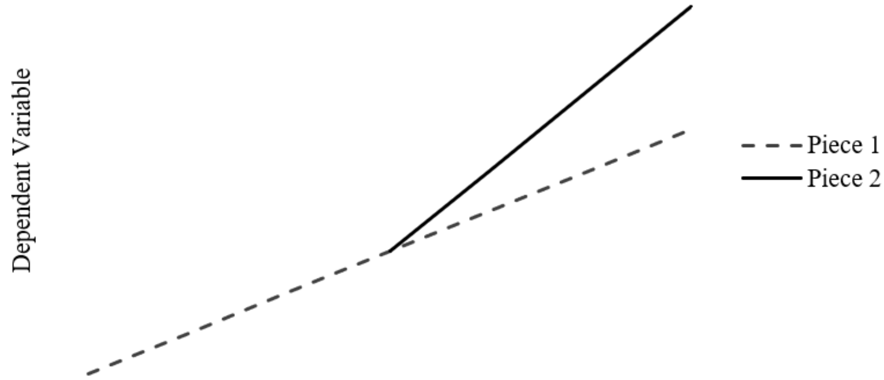
2.6 Analytic Approach

The present study had two aims. The first was to investigate how communication and coordinated communication change as infants transition from crawling to walking. We specifically focused on the frequency with which infants coordinated gestures with other communicative behaviors, specifically eye gaze and vocalizations. The second was to investigate whether the development of coordinated communication differed for infants later diagnosed with ASD. Hierarchical linear modeling (HLM) is an appropriate analytic tool for these longitudinal cross-cohort data because it assesses variance at two levels. Level 1 measures change across time points, which are nested within individual infants. Level 2 assesses variability in model terms (i.e., the intercept and slope terms) across individual infants, nested within outcome groups.

An additional benefit of HLM is that it can accommodate missing or unequally spaced data (e.g., Huttenlocher, Haight, Bryk, Seltzer & Lyons, 1991; Singer, 1998). This is particularly useful for the current sample, as 674 out of 812 possible observations (83.0%) were completed. Additionally, missingness was greater among the HR (81% complete) than the LR sample (96% complete). This was because 7 HR infants enrolled into the study late, and attrition and missed visits were greater among HR infants than LR infants. However, there were no differences in missingness among the HR outcome groups (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).

2.6.1 Model Selection

My selection protocol for identifying models that best fit the data for each variable was as follows. First, I calculated four unconditional models (i.e., with no Level-2 predictors such as Outcome Group), which included an intercept-only, linear, quadratic, and piecewise model. The first unconditional model was an intercept-only model which includes no slope terms. Thus, this type of model reflects data for which there is no change over time. Second, I calculated the unconditional linear model with TIME as a Level-1 predictor. Next, we calculated the unconditional quadratic model which includes both a TIME and a $TIME^2$ Level-1 predictor. Finally, we fitted an unconditional piecewise model. In this type of model, as illustrated in Figure 1, time is treated not as one continuous measure but as two pieces. The first slope term, PIECE 1, models time across all sessions. The second, PIECE 2, models time beginning at the final crawling-only session.



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

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

[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.

For each dependent variable, we used the unconditional models described above to determine which was the best and most parsimonious fit to the observed data. We compared fit among each of the four models using a chi-square deviance test. This test reports a deviance score for each model, where a greater value denotes greater deviance of the raw data from the model estimates (i.e., worse fit). Higher-order models—those with more model terms—were selected only if they showed significantly less deviance than lower-level models and the additional model term was significant. This process led us to select only linear and piecewise models.

2.6.2 Final Conditional Models

Final Linear Models. A linear model was determined to best fit the data for gestures without vocalizations and gestures without gaze. In these 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 Piecewise Models. Piecewise models best fit the data for gestures coordinated with vocalizations and gestures coordinated with gaze. For these 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 (π0i) 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 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. To test for differences between HR groups, we recalculated the models and rotated the reference group.

3.0 RESULTS

This study investigated how coordinated communication changes as infants transition from crawling to walking. It also explored how coordinated communication across this transition may differ among HR infant groups. For the purpose of this study, coordinated communication included the coordination of gestures and vocalizations, as well as the coordination of gestures and eye gaze.

3.1 Coordination of Gestures and Vocalizations

Descriptive statistics for the frequencies of infants' production of gestures both coordinated with and produced without vocalization are presented in Table 3.

Table 3. Descriptive Statistics for Gesture Coordination with Vocalizations

		LR			HR-ND			HR-LD			HR-ASD		
	Time	*M*	*SD*	*range*	*M*	*SD*	*range*	*M*	*SD*	*range*	*M*	*SD*	*range*
Gesture +Voc	-3	0.42	1.02	0-4	1.02	2.50	0-14	1.30	2.13	0-8	0.50	0.91	0-3
	-2	1.00	1.32	0-4	1.22	1.79	0-8	1.19	1.29	0-5	1.00	1.68	0-5
	-1	1.48	2.47	0-10	1.41	1.97	0-8	1.00	1.38	0-4	1.38	1.76	0-5
	0	1.62	2.26	0-10	1.66	2.51	0-12	1.48	1.95	0-6	1.00	1.10	0-3
	1	2.60	2.42	0-9	3.18	5.00	0-27	2.82	2.91	0-9	1.00	1.67	0-5
	2	4.32	3.21	0-13	4.97	4.95	0-21	1.85	1.82	0-6	1.60	2.55	0-8
	3	5.71	4.46	0-16	4.15	5.03	0-22	3.27	3.23	0-10	2.44	4.42	0-14
Gesture-without-Voc	-3	1.54	1.91	0-8	2.07	2.84	0-11	3.15	5.88	0-27	1.33	1.97	0-6
	-2	2.44	3.87	0-15	2.33	2.52	0-13	4.05	6.65	0-26	2.69	1.80	1-6
	-1	3.00	3.67	0-10	2.27	2.50	0-12	2.82	3.55	0-15	2.38	2.43	0-8
	0	3.00	3.121	0-13	2.52	2.22	0-9	3.26	3.00	0-10	2.00	2.10	0-7
	1	4.16	4.95	0-17	3.04	2.87	0-13	3.64	3.72	0-13	3.18	2.23	0-8
	2	3.64	3.38	0-13	3.21	3.12	0-12	3.62	3.91	0-10	2.10	2.56	0-7
	3	5.04	6.00	0-24	3.58	4.44	0-21	2.36	2.11	0-6	2.67	1.00	1-4

3.1.1 Gestures with Vocalizations

Trajectories for the frequency of infants' coordination of gestures and vocalizations were fitted with a piecewise model; these coefficients are presented below in Table 4.

Estimated trajectories for the frequency of gesture-vocalization (hereafter referred to as "Gesture+Voc") coordinations are presented in Figure 2. LR infants showed significant growth throughout the observed period, as well as significant additional growth after walk onset. This pattern is confirmed by model estimates. Prior to walk onset, LR infants increased by 0.433 Gesture+Voc combinations per month ($p = 0.017$). Following walk onset, this growth increased to a rate of 1.665 Gesture+Voc combinations per month (0.433 Gesture+Voc combinations per month baseline growth + 1.232 Gesture+Voc combinations per month additional incremental growth). Thus, at the initial timepoint, LR infants produced an estimated 0.833 Gesture+Voc combinations. By the final timepoint, they produced 5.829 Gesture+Voc combinations. The HR-ND and HR-LD groups did not differ significantly from the LR group on any model terms (*p*s ≥ 0.150)

The HR-ASD infants did not differ from LR infants in their baseline slope or their production of Gesture+Voc at the intercept (i.e., the final crawl-only session; *p*s ≥ 0.064). However, HR-ASD infants showed less additional growth after walk onset ($p = 0.028$). While the LR group showed additional growth of 1.232 Gesture+Voc combinations per month, the HR-ASD infants' trajectory remained relatively flat. HR-ASD infants produced 0.900 Gesture+Voc combinations at the final crawling visit and only 1.006 at the final walking visit —virtually the same rate of production. Thus, by the final timepoint, HR-ASD infants produced 4.823 fewer Gesture+Voc combinations overall relative to LR infants. HR-ASD infants did not significantly differ from the HR-LD group on any model terms.

Table 4. Model Estimates for Infant Coordination of Gestures and Vocalizations

	Coefficient	Standard error	p-value
Intercept, π_0			
LR intercept, β_{00}	2.133	0.462	<0.001
Age at walk onset, β_{01}	0.554	0.204	0.008
HR-ND, β_{02}	0.102	0.497	0.837
HR-LD, β_{03}	-0.933	0.644	0.150
HR-ASD, β_{04}	-1.233	0.658	0.064
Piece 1 slope, π_1			
LR slope, β_{10}	0.433	0.179	0.017
Age at walk onset, β_{11}	0.0778	0.050	0.125
HR-ND, β_{12}	-0.041	0.189	0.826
HR-LD, β_{13}	-0.315	0.235	0.182
HR-ASD, β_{14}	-0.272	0.216	0.210
Piece 2 slope, π_2			
LR slope, β_{20}	1.23	0.448	0.007
Age at walk onset, β_{21}	0.226	0.145	0.122
HR-ND, β_{22}	-0.032	0.475	0.946
HR-LD, β_{23}	-0.611	0.598	0.309
HR-ASD, β_{24}	-1.197	0.538	0.028

Note: df = 110; the intercept in this model is the midpoint of the trajectory

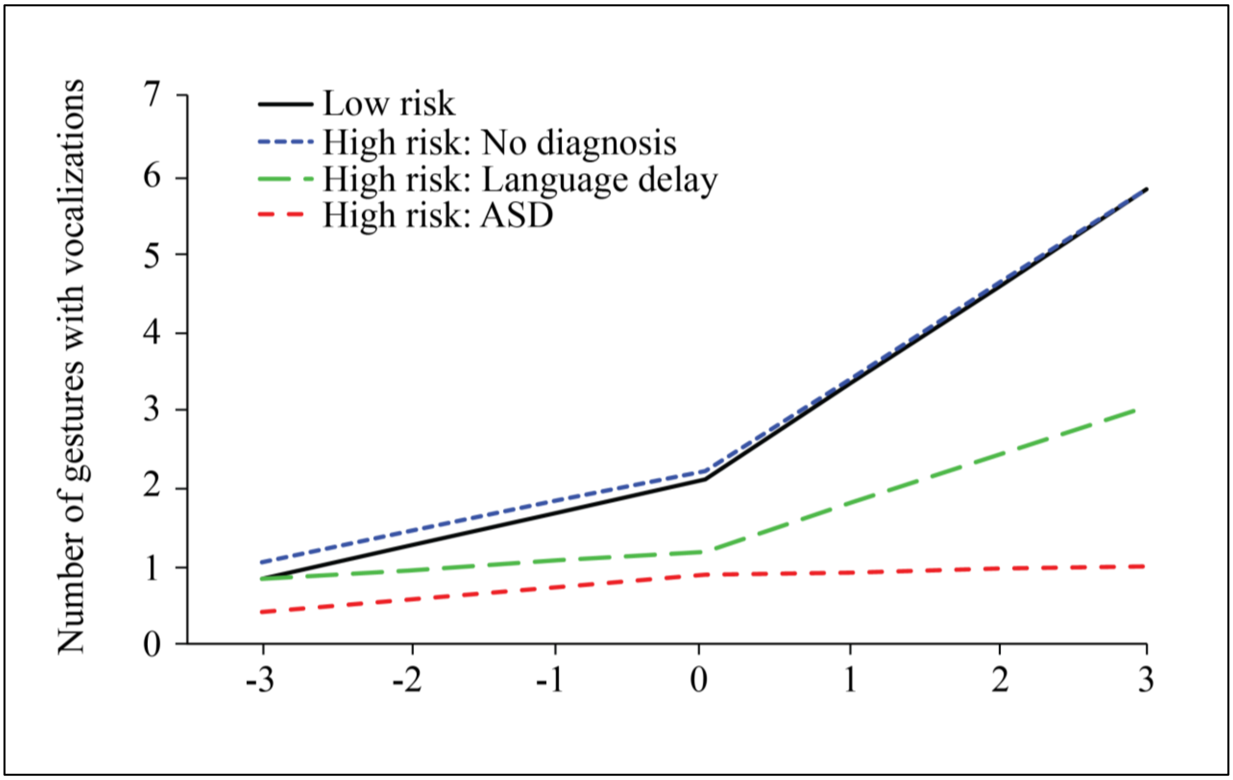


Figure 2. Model Projections for Infant Coordination of Gestures and Vocalizations

3.1.2 Gestures without Vocalizations

Trajectories for the frequency of infants' production of gestures without vocalizations (hereafter, "Gesture-no-Voc") were fitted with a linear model; estimations are presented in Figure 3. Coefficients are presented below in Table 5.

Table 5. Model Estimates of Infant Production of Gestures Without Vocalizations

	Coefficient	Standard error	p-value
Intercept, π_0			
LR intercept, β_{00}	3.420	0.466	<0.001
Age at walk onset, β_{01}	0.208	0.124	0.097
HR-ND, β_{02}	-0.586	0.523	0.265
HR-LD, β_{03}	-0.1022	0.739	0.890
HR-ASD, β_{04}	-1.10	0.562	0.053
Linear slope, π_1			
LR slope, β_{10}	0.523	0.159	0.001
Age at walk onset, β_{11}	0.036	0.032	0.268
HR-ND, β_{12}	-0.249	0.182	0.175
HR-LD, β_{13}	-0.467	0.339	0.171
HR-ASD, β_{14}	-0.378	0.188	0.047

Note: df = 110; the intercept in this model is the midpoint of the trajectory

Across the observation period, LR infants steadily increased their instances of Gesture-no-Voc by 0.523 per month, representing substantial change over time (p = 0.001). At the initial timepoint, LR infants produced an estimated 1.851 bouts of Gesture-no-Voc. By the final timepoint, this value grew to 4.988 bouts of Gesture-no-Voc. The HR-ND and HR-LD groups did not significantly differ from the LR group on any model terms (ps ≥ 0.171).

While the HR-ASD infants did not significantly differ from LR infants at the intercept (p = 0.053), they did show less growth overall (p = 0.047), increasing by only 0.145 instances of Gesture-no-Voc per month. By the final timepoint, the HR-ASD infants produced only 2.754 bouts of Gesture-no-Voc—about half as many as the LR infants. HR-ASD infants did not significantly differ from the HR-LD group on any model terms.

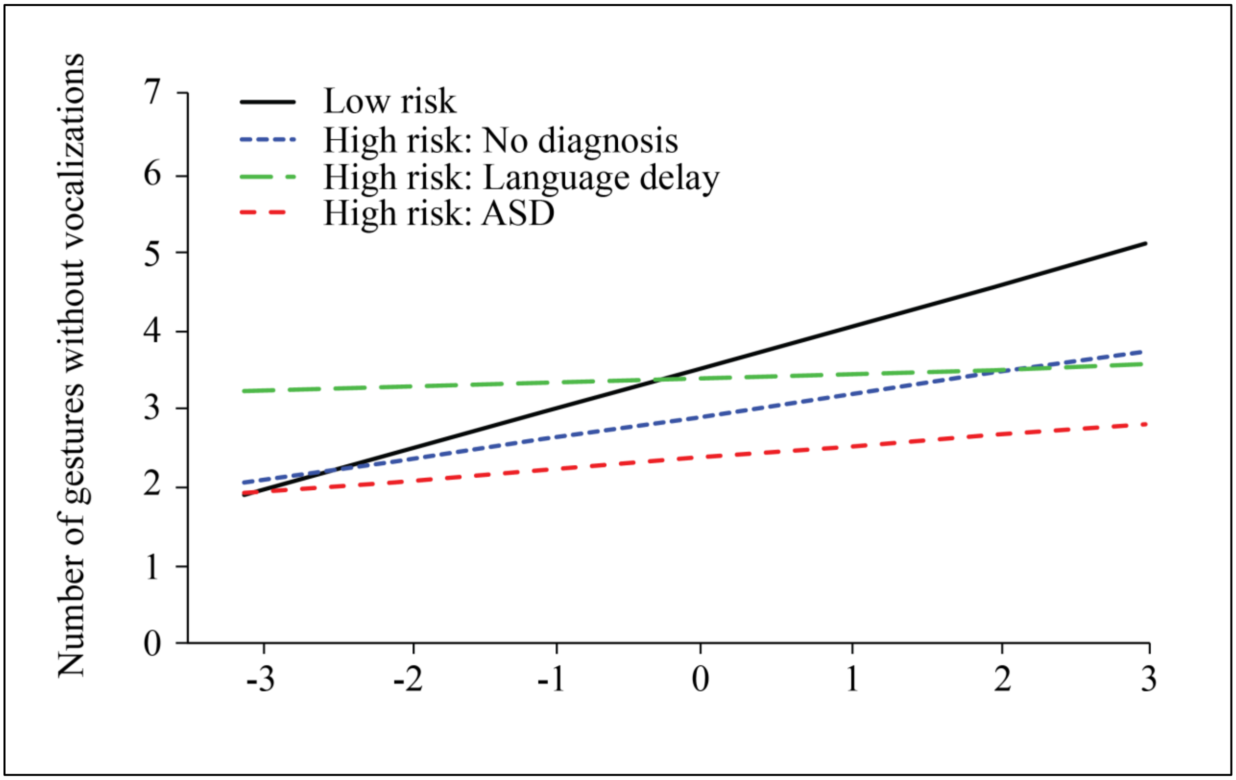


Figure 3. Model Projections for Infant Production of Gestures Without Vocalizations

3.1.3 Summary

Across the transition from crawling to walking, neurotypical infants substantially increased their production of Gesture+Voc and Gesture-no-Voc. However, the trajectories of these behaviors were substantially different. For Gesture+Voc, the months following walk onset marked a time of significant additional growth, increasing by about six-fold for LR and HR-ND infants. Conversely, for Gesture-no-Voc, growth was steady across the entire period of observation, which was evident by the fact that a linear model best fit the data.

In contrast to LR infants, HR-ASD infants showed considerably flatter growth for both gesture types. In their production of Gesture+Voc, the HR-ASD infants had substantially less growth following walk onset. At the final timepoint, the LR infants produced 5.829 Gesture+Voc combinations, while—strikingly—HR-ASD infants only produced 1.006. In terms of Gesture-no-Voc production, HR-ASD again displayed less growth overall compared to LR infants. Although HR-ASD infants' production of both types of communication differed substantially from that of LR infants, they did not differ significantly from their HR-LD peers.

3.2 Coordination of Gestures and Gaze

Descriptive statistics for the frequency of infants' production of gesture both coordinated with and produced without vocalization are presented in Table 6.

Table 6. Descriptive Statistics for Gesture Coordination with Gaze

		LR			HR-ND			HR-LD			HR-ASD		
	Time	*M*	*SD*	*range*	*M*	*SD*	*range*	*M*	*SD*	*range*	*M*	*SD*	*range*
Gesture +Gaze	-3	1.00	1.87	0-9	1.87	3.17	0-17	1.95	3.65	0-16	1.00	1.13	0-3
	-2	1.36	2.18	0-9	1.85	2.15	0-11	2.57	4.17	0-18	2.23	1.83	0-5
	-1	1.00	1.32	0-5	1.73	2.37	0-12	2.55	3.71	0-16	1.85	1.77	0-5
	0	1.83	2.22	0-8	1.91	2.07	0-9	2.39	3.04	0-11	2.09	2.84	0-10
	1	3.12	3.77	0-15	3.04	4.98	0-32	3.18	4.06	0-18	2.18	2.52	0-7
	2	3.12	3.77	0-16	3.79	4.14	0-15	1.85	1.73	0-5	1.90	2.18	0-6
	3	4.79	4.45	0-17	3.85	5.79	0-23	2.00	1.41	0-4	1.22	0.67	0-2
Gesture-without-Gaze	-3	0.96	1.30	0-5	1.22	2.30	0-10	2.50	4.38	0-19	0.83	1.27	0-4
	-2	2.08	3.34	0-15	1.70	2.14	0-10	2.67	4.21	0-16	1.46	0.97	0-3
	-1	3.48	4.94	0-17	1.95	1.80	0-8	1.27	1.80	0-6	1.92	2.22	0-6
	0	2.79	3.01	0-10	2.27	2.40	0-11	2.35	2.25	0-9	0.91	1.14	0-3
	1	3.64	3.26	0-14	3.18	3.41	0-18	3.27	4.01	0-19	2.00	2.65	0-9
	2	4.84	3.90	0-17	4.39	4.17	0-17	3.62	4.56	0-16	1.80	3.80	0-12
	3	5.96	5.85	0-27	3.88	4.00	0-14	3.64	3.59	0-10	2.78	2.64	0-9

3.2.1 Gestures with Gaze

Trajectories for the frequency of infants' coordination of gestures and eye gaze (hereafter, Gesture+Gaze) were fitted with a piecewise model. Coefficients are presented in Table 7.

Table 7. Model Estimates of Infant Coordination of Gestures and Gaze

	Coefficient	Standard error	p-value
Intercept, π_0			
LR intercept, β_{00}	1.903	0.397	<0.001
Age at walk onset, β_{01}	0.199	0.267	0.458
HR-ND, β_{02}	0.374	0.431	0.388
HR-LD, β_{03}	0.665	0.825	0.422
HR-ASD, β_{04}	0.438	0.786	0.579
Piece 1 slope, π_1			
LR slope, β_{10}	0.268	0.188	0.157
Age at walk onset, β_{11}	0.007	0.052	0.886
HR-ND, β_{12}	-0.131	0.208	0.529
HR-LD, β_{13}	-0.038	0.253	0.882
HR-ASD, β_{14}	0.139	0.311	0.657
Piece 2 slope, π_2			
LR slope, β_{20}	0.949	0.292	0.002
Age at walk onset, β_{21}	0.246	0.107	0.024
HR-ND, β_{22}	-0.103	0.396	0.794
HR-LD, β_{23}	-1.221	0.438	0.006
HR-ASD, β_{24}	-1.585	0.583	0.008

Note: df = 110; in the model, the intercept is the midpoint of the trajectory

Estimated trajectories for the frequency of Gesture+Gaze are presented in Figure 4. Prior to walk onset, LR infants increased by 0.268 Gesture+Gaze combinations per month ($p = 0.157$). Following walk onset, production of these gestures increased to a rate of 1.217 per month (0.268 Gesture+Gaze combinations per month baseline growth + 0.949 combinations per month additional incremental growth). LR infants produced an estimated 1.098 Gesture+Gaze combinations at the initial timepoint and increased to 4.749 by the final timepoint. HR-ND infants did not significantly differ on any model terms (ps ≥ 0.388).

HR-LD and HR-ASD infants did not differ significantly from LR infants in their baseline slope ($ps \geq 0.657$) or their production of Gesture+Gaze at the intercept (i.e., final crawl-only session; $ps \geq 0.422$). However, HR-LD and HR-ASD infants did show less additional growth when they began to walk ($ps \leq 0.008$). In contrast to LR infants, growth for HR-LD and HR-ASD infants remained relatively flat. In fact, neither the HR-LD nor HR-ASD groups increased at all from the final crawling visit (i.e., the midpoint) to their final walking visit (see Figure 4). By the final timepoint, HR-LD infants produced 2.999 fewer Gesture+Gaze combinations overall than LR infants. Strikingly, HR-ASD infants produced 4.954 fewer Gesture+Gaze combinations overall than LR infants. However, HR-ASD infants did not significantly differ from the HR-LD group on any model terms.

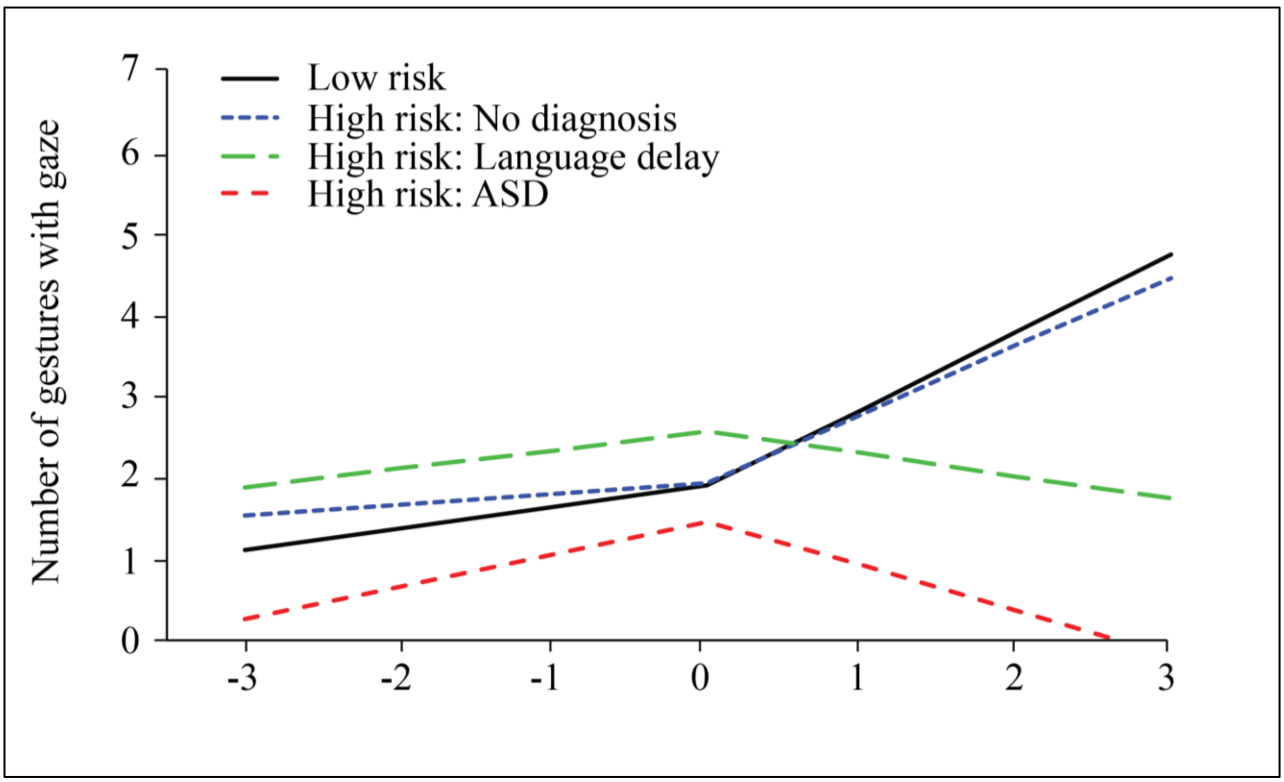


Figure 4. Model Projections for Infant Coordination of Gestures and Gaze

3.2.2 Gestures without Gaze

Trajectories for the frequency of infants' production of gestures without gaze (hereafter, Gesture-no-Gaze) were fitted with a linear model. Coefficients are presented in Table 8.

Table 8. Model Estimates of Infant Production of Gestures Without Gaze

	Coefficient	Standard error	p-value
Intercept, π_0			
LR intercept, β_{00}	3.872	0.477	<0.001
Age at walk onset, β_{01}	0.520	0.136	<0.001
HR-ND, β_{02}	-0.928	0.514	0.074
HR-LD, β_{03}	-1.290	0.651	0.050
HR-ASD, β_{04}	-2.343	0.576	<0.001
Linear slope, π_1			
LR slope, β_{10}	0.802	0.171	<0.001
Age at walk onset, β_{11}	0.071	0.033	0.034
HR-ND, β_{12}	-0.184	0.191	0.337
HR-LD, β_{13}	-0.490	0.307	0.113
HR-ASD, β_{14}	-0.530	0.223	0.019

Note: df = 110; in the model, the intercept is the midpoint of the trajectory

Estimated trajectories for the frequency of production of Gesture-no-Gaze are presented in Figure 5. Across the period of observation, LR infants steadily increased their frequency of Gesture-no-Gaze production (p = <0.001). At the initial visit, LR infants produced an estimated 1.467 bouts of Gesture-no-Gaze. By the final timepoint, the LR infants produced an estimated 6.277 of these gestures—approximately quadrupling their frequency of production. The HR-ND infants did not differ significantly from the LR group on any model terms (ps ≥ 0.074). HR-LD infants produced significantly fewer instances of Gesture-no-Gaze than LR infants at the intercept (p = 0.050), but did not differ in their slope (p = 0.113).

In comparison to LR infants, HR-ASD infants significantly differed in their production of Gesture-no-Gaze at the final crawling session (p < 0.001). In addition to differing at the intercept, HR-ASD also showed substantially less growth overall (p = 0.019). While LR infants increased by 0.802 bouts of Gesture-no-Voc each month, HR-ASD infants only increased by 0.272 monthly. HR-ASD infants did not significantly differ from the HR-LD group on any model terms.

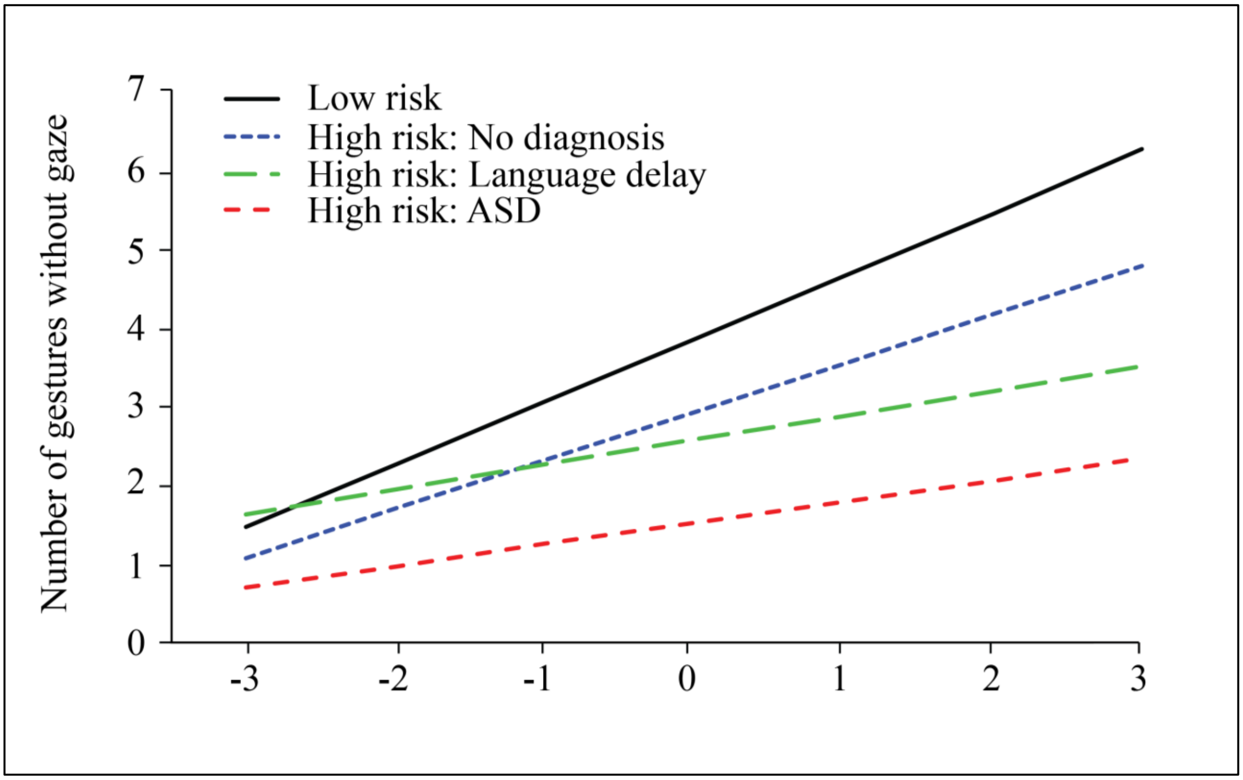


Figure 5. Model Projections for Infant Production of Gestures Without Gaze

3.2.3 Summary

As neurotypically developing infants transitioned from crawling to walking, they increased their production of gestures—both with and without gaze. The onset of walking was further accompanied by *additional* growth in Gesture+Gaze for the LR and HR-ND infants, such that production of Gesture+Gaze quadrupled by the end of the observed period. A different pattern was observed for Gesture-no-Gaze. While typically developing infants increased their production of Gesture-no-Gaze over time, growth was linear. In other words, the selection of a linear model denotes that walk onset did *not* mark a time of significant additional growth for production of Gesture-no-Gaze in neurotypical infants.

HR-LD and HR-ASD infants showed a different pattern compared to the LR comparison group. Production of Gesture+Gaze remained relatively flat for both groups. It was even estimated that HR-ASD infants were not producing any instances of Gesture+Gaze by the end of the observed period, whereas the LR group produced an estimated 4.749 Gesture+Gaze combinations during that same month. This highlights another instance of HR-ASD infants differing from neurotypically developing peers in their development of coordinated communication, but they did not differ from HR-LD infants, who were producing approximately 1.751 Gesture+Gaze combinations by the final timepoint.

4.0 DISCUSSION

This research was designed to investigate the development of coordinated communication in infants across the transition from crawling to walking. The study followed LR and HR infant groups longitudinally as they began to walk, and compared three outcome groups of HR infants (HR-ND, HR-LD, HR-ASD) at 36 months. There were two main findings. First, for neurotypical infants, walk onset marked a point of inflection for gestures coordinated with vocalizations and with gaze, but not for uncoordinated gestures. Second, HR-ASD infants showed different developmental trajectories than their HR-ND peers: HR-ASD displayed attenuated growth across all types of gestures, and walking was *not* accompanied by increased growth in coordinations, as it was for neurotypical infants. A similar pattern was also observed among HR-LD infants.

4.1 Communication Becomes More Coordinated with Walking in Neurotypical Development

Prior work shows that walking is accompanied by an increased frequency of communication in neurotypical infants (e.g., Clearfield, 2011; Walle, 2016; West, 2019). The present study extends these findings, showing that communication becomes more *coordinated* when neurotypical infants begin to walk. Specifically, infants display a spurt in their production of vocalization- and gaze-coordinated gestures at walk onset. While uncoordinated gestures also increased during this transition period, walk onset was not a point of inflection for their growth. Thus, with the onset of walking, communication not only becomes more frequent but also more sophisticated as infants combine communicative behaviors like gestures and vocalizations into a single communicative act.

This spurt in coordination may have a cascading effect on infants' social interactions (e.g., Donnellan et al., 2020; Goldin-Meadow et al., 2007). Coordinated communication is more salient to caregivers and more likely to elicit rich social and verbal input (e.g., Crais et al., 2009; Donnellan et al., 2020; Goldin-Meadow et al., 2007). For example, Goldin-Meadow and colleagues (2007) found that caregivers increased the length of their sentences when the infant produced a gesture-vocalization combination, as opposed to an isolated gesture or isolated vocalization. In particular, pairing a vocalization with a gesture makes the gesture more noticeable. Behaviors like gestures or gaze require the caregiver to visually monitor the infant in order to notice them. However, pairing a vocalization may alert caregivers to the infant's communicative bid, particularly when they are distracted or looking away (Gros-Louis et al., 2006). Thus, the spurt in coordinated communication at walk onset may have a cascading effect on caregivers' verbal responses to infants. And in fact, West (2019) reported that caregivers' verbal responses to infants' communicative attempts increase with the advent of walking.

To take the cascade one step further, if caregiver verbal responses change at walk onset, this could open opportunities for infants to learn language (Bang & Nadig, 2015; Donnellan et al., 2020; Tamis-LeMonda et al., 2001). Notably, prior work has shown that neurotypical infants display a spurt in word learning when they start walking (He et al., 2016; Walle & Campos, 2014; West et al., 2018). Here, study findings provide possible insight into *why* language changes with walk onset. Walking may instigate a developmental cascade: as infant communication becomes more coordinated, caregivers have opportunities to provide richer verbal input, which in turn may influence infants' language learning. Given the changes in communication surrounding walk onset, a more holistic account of infant development is necessary to better understand how communication develops, particularly within the context of motor development.

4.2 For Infants with ASD, Communication Does Not Change with Walking

While neurotypical infants' communication became more coordinated across the transition to walking, HR-ASD infants displayed a different pattern of growth. Learning to walk did not appear to provide an additional boost in coordinated communication for HR-ASD infants as it did for neurotypical infants.

Prior work has shown that children with ASD display difficulties integrating multiple communicative behaviors, relying on isolated communicative behaviors instead (e.g., Shumway & Wetherby, 2009; Stone et al., 1997; Wetherby et al., 1989). For example, Wetherby and colleagues (1989) reported that, compared to their neurotypical peers, preschoolers with ASD produced a higher proportion of isolated gestures and a lower proportion of gesture-vocalization combinations. Similarly, in a study of toddlers matched on chronological age, mental age, and expressive vocabulary, children with ASD produced a significantly lower proportion of communicative acts involving gestures, gaze, and vocalizations than those without ASD (Stone et al. 1997). While prior work has shown that preschoolers with ASD display difficulties integrating multiple communicative acts (e.g., Shumway & Wetherby, 2009; Stone et al., 1997; Wetherby et al., 1989), the present study adds to a growing body of literature indicating that these differences in coordinated communication begin in infancy (e.g.,; Choi et al., 2019; Heymann et al., 2018; Parladé and Iverson, 2015).

As previously described, coordinated communication is an important component of language development due to its relative complexity and increased salience compared to isolated communicative behaviors (e.g., Crais et al., 2009; Donnellan et al., 2020; Goldin-Meadow et al., 2007). What happens for HR-ASD infants who do not increase the frequency of coordinated communication by more than one bout per month? At a time when neurotypical infants benefit from the developmental cascade of producing more salient gestures, eliciting richer verbal input, and experiencing gains in language learning, HR-ASD infants may fall further behind in their language development.

A variety of compounding factors may contribute to the break in developmental cascade that neurotypical infants experience. In contrast to neurotypical infants, HR-ASD infants produce fewer gestures overall as they learn to walk (West, 2019). The current study showed that HR-ASD infants' gestures were also less coordinated during this transition period. With decreased production of these highly salient communicative bids, parents may have fewer opportunities to provide contingent responses to infants' communication attempts. This is especially concerning given that infants with ASD are already known to be vulnerable to delays and difficulties in language (e.g., Hudry et al., 2014; Iverson et al., 2018; Mitchell et al., 2006). In a time filled with potential to receive richer caregiver input as a product of this developmental cascade, HR-ASD infants' lack of growth in coordinated communication may make them vulnerable to falling even further behind in their language development.

A unique feature of this study was the inclusion of a group of HR infants with delayed language development but no ASD diagnosis. In this study, the HR-LD infants nearly always fell between LR and HR-ASD infants in terms of their gesture growth, such that they never significantly differed from HR-ASD infants in their growth following walk onset. Thus, attenuated growth in coordinated communication at walk onset appears to be characteristic of—but not specific to—infants with ASD, and it may be limited in distinguishing ASD from other types of developmental delay.

4.3 Limitations

The current study has a number of strengths. Most importantly, the intersection between motor development and communication in infants with ASD has been understudied—especially coordinated communication, and this study helped bridge that gap in our knowledge. It featured naturalistic observations and a longitudinal design that provided the ability to identify and highlight the seven months surrounding the onset of walking for each infant. Additionally, it included a large sample of HR infants (n = 91), which gave us the opportunity to observe subgroups of HR infants with different developmental outcomes (i.e., HR-ND, HR-LD, HR-ASD) and provided insight into developmental differences between HR infants with vs. without an ASD diagnosis. However, there are some limitations worth noting.

First, the sample size for the HR-ASD infants was relatively small (n = 15), though this is common in studies of HR infants (e.g., Gangi et al., 2014; Ozonoff et al., 2010; Winder et al., 2013). Secondly, the study focused on only 10 minutes of free play at each monthly visit. A longer window of observation could have provided higher baseline frequencies of gestures during a wider range of activities as infants and caregivers go about daily routines.

Lastly, it is unclear whether infants *intend* to coordinate behaviors together, or alternatively whether increased coordinated is due to elevated base rates of each individual behavior. Regardless of whether behaviors are coordinated because of infants' intention or by chance, the increase in coordination is still meaningful. As previously discussed, caregivers are more likely to respond to coordinated communication than to single communicative behaviors (e.g., Crais et al., 2009; Donnellan et al., 2020; Goldin-Meadow et al., 2007; Martinsen & Smith, 1989). Thus, regardless of the infant's intention, an increase in coordinated communication likely prompts a parallel increase in rich verbal responses.

4.4 Clinical Implications

Though many infants with ASD have been shown to make developmental gains in intensive early intervention, no conclusions can be made yet regarding which approach is most effective (Warren et al., 2011). The results of this study have the potential to influence decisions regarding early intervention approaches and positively impact client progress. Heymann et al. (2018) suggested that current early intervention approaches which focus generally on increasing infants' communicative behaviors may further improve by focusing on promoting the coordination of multiple communicative behaviors. Additionally, intervention approaches may benefit from coaching caregivers to provide rich verbal input to less salient or advanced forms of communication, given that infants with ASD are less likely to coordinate joint attention and vocalizations and produce less advanced gestures (Heymann et al., 2018; Leezenbaum et al., 2014).

While there are a number of different early intervention strategies available for infants with ASD, many have found success in emphasizing the global nature of infant development. For example, The Early Start Denver Model (ESDM; Rogers & Dawson, 2010) aims to increase development across multiple domains (e.g., joint attention, language, motor skills, play) for children with ASD. In a randomized, controlled trial of an intervention for toddlers with ASD, Dawson et al. (2010) reported that, compared with children who received community intervention, children who received the ESDM showed significant improvements in IQ, adaptive behavior, and autism diagnosis. Others have found similar success with the ESDM, such as Colombi et al. (2018) who reported significant gains in overall developmental quotient and language in the ASD group that received ESDM intervention. Harbourne and colleagues' (2018) "Sitting Together and Reaching to Play" (START-Play) approach to intervention utilizes improvements in motor skills to scaffold social and object interactions, again viewing specific developmental domains in a broader context (see also Lobo et al., 2013).

Currently, young children with ASD often receive interventions (e.g., speech-language therapy, physical therapy) in isolation from other areas of development. This study adds to a growing body of literature (e.g., Dawson et al., 2010; Harbourne et al., 2018; Lobo et al., 2013) that supports a philosophy of comprehensive and collaborative treatment strategies, especially those integrating both motor-based approaches (e.g., physical therapy) and communication-focused approaches (e.g., speech-language therapy). These comprehensive approaches often require rigorous training and a considerable amount of resources (e.g., Baril & Humphreys, 2018). However, results of this study, which highlight how communication and motor development are intertwined, and positive results from these approaches (e.g., Colombi et al., 2016; Harbourne et al., 2018; Lobo et al., 2013) suggest that they are effective and worthwhile.

Appendix A Infant Communication Coding Manual

Appendix A.1 Gestures and Direction

<u>Deictic Gestures</u>

1. *Give*: infant hands an object to a social partner
2. *Show*: infant holds up an object to show a social partner
3. *Reach*: infant reaches for an out-of-reach object
4. *Index finger point*: infant point to an object with an isolated index finger
5. *Index finger touch*: infant touches an object with an isolated index finger
    a. Does not count for buttons

Subsequent codes are categorizing some dimension of these identified gestures.

<u>Direction</u>

If during the gesture, the infant was looking at the social partner, code as “directed”. Otherwise, code as “undirected”

<u>Notes</u>

1. About reaches:
    a. For a new reach to start, the arm/hand must be retracted in between
    b. If two reaches occur back-to-back for the same object, there must be at least a one second pause between them.
    c. In order to count as a reach, the infant can’t successfully make contact with the object on their own (however, it’s ok if parent hands them object).
2. About points:

   a. In general, be conservative about when to code “point”. Index finger must be very clear.
3. About gives:
   a. Don’t count as “give” if baby is throwing a ball back and forth—no matter the form (e.g., overhand, swipe, etc.)
4. About direction:
   a. You don’t have to be able to see the face to code as directed, if you feel confident from the head position
   b. However, if you’re really on the fence, code as “undirected” to be conservative
   c. Gaze doesn’t have to be specifically to the face, they can be looking at any part of the social partner to count as “directed”
   d. Sometimes you know where an out-of-frame person is based on a previous angle. You can use this information to establish whether a gesture is directed, but only if it occurred either 5 seconds before or after the gesture.

Appendix A.2 Vocalizations

<u>Vocalizations</u>

1. Non-word vocs: sounds produced by the infant
   a. NOT vegetative sounds: sneezing, coughing, breathing
   b. NOT affective sounds: laughing, fussing, crying
2. Vocs with words: vocs that contain either an English word or a speech sound consistently used to refer to an object (e.g., “bah-bah” to refer to a bottle).

Notes

1. About identifying non-word vocs:
    a. If a voc is immediately prefaced or followed by a cry without a clear pause, don't code it.
    b. There must be at least a one second pause between vocs (i.e. if pause is less than 1 second, count as one long voc).
    c. If baby is feeding or drinking, only code VERY clear vocs
    d. Do code raspberries
2. About identifying words:
    a. In general, be conservative about coding words. If you can't clearly hear what it is, don't code it as a word.
    b. Animal sounds count as words.

Appendix A.3 Coordination of Gesture and Vocalization

Coordination communication will be defined as a combination of a previously identified deictic gesture and a previously identified vocalization

1. Gesture: give, show, reach, index finger (IF) point, index finger (IF) touch
2. Vocalization: non-word voc ("NWV"), voc with words ("word")

Coordinated Communication

1. *Simultaneous* (y): overlap between gesture and vocalization or within 0.5 seconds
2. *No coordination* (n): no vocalization occurs during a gesture or within 0.5 seconds

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