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ORIGINAL PAPER

Trajectories of Posture Development in Infants With and Without Familial Risk for Autism Spectrum Disorder

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Abstract
This study investigated early posture development prospectively in infants at heightened (HR) vs. low risk (Low Risk; LR) for ASD. Fourteen HR infants diagnosed with ASD (HR-ASD), 17 HR infants with language delay (HR-LD), 29 HR infants with no diagnosis (HR-ND), and 25 LR infants were videotaped at home for 25 min during everyday activities and play at 6, 8, 10, 12, and 14 months. All postures were coded and the sustainment source was identified for supported postures. Relative to LR infants, HR-ASD infants and to a lesser extent HR-LD infants exhibited distinct postural trajectories that revealed slower development of more advanced postures. In addition, subtle differences in posture sustainment differentiated HR-ASD from HR-LD infants.

Keywords Infant siblings · Autism spectrum disorder · Posture · Motor development

Introduction

For typically developing (TD) infants, the first year and a half of life is marked by dramatic advances in posture development. As infants progressively gain greater strength and become better able to integrate vestibular and proprioceptive information continuously with ongoing motor activity to control postural sway, they transition from postures in which they are fully supported by a surface (i.e., prone and supine lying) to postures that are more biomechanically challenging (i.e., unsupported sitting, hands and knees, standing).

The emergence and consolidation of new postures dramatically change infants' experiences with objects, people, and their own bodies in ways that create opportunities for learning and development outside the motor area (see Iverson 2010, for a review). For example, the progression from lying postures (prone on the belly, supine on the back) to sitting creates a more biomechanically supportive context for infant arm movement (see Out et al. 1998). When infants are supine, the arm's center of mass is mostly above the center of rotation, which generates instability because the force of gravity amplifies every perturbation in the arm's position. In sitting, however, the arm's center of mass is mostly below the center of rotation; position perturbations are counteracted by gravity and the arm is relatively stable. These gains in stability relate directly to changes in infant reaching (Hopkins and Rönnqvist 2002; Carvalho et al. 2007, 2008).

The progression from lying to sitting also influences object exploration. In supine, arm movements are more effortful and less easily controlled as infants must constantly work against gravity to hold an object within the line of sight. In prone, infants must prop their chests up using an arm or hand and keep their heads raised continuously in order to see the object, which is often fatiguing. When seated, however, hands and arms are free to move in less biomechanically challenging ways; the upright head position enlarges the field of view and stabilizes gaze, thereby promoting eye-hand coordination (Bertenthal and von Hofsten 1998; Rochat 1992); and possibilities for object exploration are enhanced (e.g., Rochat and Goubet 1995; Soska and Adolph 2014). Thus, posture development is not only an index of advancing motor control; it is also as a catalyst for enriching the conditions of object exploration, shared

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attention, and early communication development (e.g., LeBarton and Iverson 2016).

Considering that the timing and progression of major posture milestones are well documented during the first year in typical development and the fact that posture disturbances are common in children and adults with autism spectrum disorder (ASD; Bhat et al. 2011; Fournier et al. 2010), delays and/or deficits in the emergence and course of posture development may be among the earliest observable differences in infants who go on to receive an ASD diagnosis. Furthermore, given the importance of early posture skills for expanding opportunities for exploration and learning, even seemingly small disruptions in posture development may have negative cascading effects that lead to or amplify delays outside the motor domain in infants later diagnosed with ASD.

Posture Development in Infants at Risk for ASD

Research using retrospective home videos indicates that posture delays and atypicalities are apparent early in development in infants eventually diagnosed with ASD (e.g. Esposito and Venuti 2009; Ozonoff et al. 2008; Teitelbaum et al. 1998). However, because this work is limited to observations from available footage, researchers have more recently begun to focus on prospectively examining infants who are at heightened biological risk for ASD because they have an affected older sibling (High Risk; HR) and comparison groups of infants with no family history of ASD (Low Risk; LR). Studying HR infants as a method for identifying potential early indicators of risk for an eventual ASD diagnosis is ideal because relative to the ASD prevalence rate in the general population (1 in 59 children; Baio 2018), that for HR infants is much greater (1 in 6 children; Ozonoff et al., 2011). There is also growing evidence that HR infants who do not receive an ASD diagnosis are at increased risk for developmental delays as well as subclinical symptoms of ASD (e.g., Messinger et al., 2013).

To date, relatively few studies of HR infants have focused on posture development in the first 18 months. Nevertheless, they provide initial evidence of very early posture delays, with the most pronounced delays observed among those who later receive an ASD diagnosis (see also West, 2018). For example, Flanagan et al. (2012) assessed postural control during a pull-to-sit task in 6-month-old HR infants. The results revealed that HR infants later diagnosed with ASD showed head lag significantly more frequently than other HR or LR infants. Findings from Nickel et al. (2013) also suggest the presence of atypicalities in the development of postural control from 6 to 14 months among HR infants eventually diagnosed with ASD. Specifically, Nickel and colleagues reported that as compared to LR and HR infants without ASD, infants eventually diagnosed with ASD exhibited substantial delays in the emergence of more advanced postures (i.e., kneeling, squatting, and standing) and spontaneously initiated fewer posture changes over the course of the observation. Although LR and HR infants without ASD displayed similar posture development profiles in general, HR infants were slower to develop skills in sitting and standing postures.

A handful of studies have also examined gross motor performance using standardized developmental measures. Estes et al. (2015) reported that HR infants who were most severely affected by ASD at 24 months exhibited poorer gross motor performance than LR infants on the Mullen Scales of Early Learning (MSEL; Mullen 1995)[1] as early as 6 months. Landa and Garrett-Mayer (2006) found that HR infants eventually diagnosed with ASD scored significantly lower than TD infants on the Gross Motor subscale of the MSEL starting at 14 months. In contrast, Leonard et al. (2013) did not observe any ASD-specific motor delays on the MSEL between 7 and 24 months. However, relative to LR infants, HR infants as a group had significantly lower Gross Motor scores at 7 and 24 months. While HR infants with ASD scored slightly lower than HR infants without ASD at each of the age points, there were no significant differences between these groups.

While the results of these studies are informative, they are limited in three significant ways. First, much of the previous research on posture and gross motor development in HR infants has included HR infants with language delays but not ASD in a broader HR-no diagnosis outcome group due to small sample sizes. Some investigators have reported delays in this group relative to LR comparison infants (e.g., Leonard et al. 2013; Nickel et al. 2013) while others have not (Estes et al. 2015). Given that children with language impairments are often significantly delayed in early posture milestones (Trauner et al. 2000; Viholainen et al. 2002), grouping HR infants with and without language delay together may have contributed to the mixed findings regarding the presence of posture delays among HR infants without an ASD diagnosis.

The second limitation of prior research in this area is that behavior has generally been sampled at intervals that are relatively widely spaced (e.g., 6, 12, 18 months). As Adolph et al. (2008) have demonstrated, when behavior is sampled with insufficient frequency, the inferred trajectories may not accurately depict the true nature of behavioral change over. Observations at regular, frequent intervals are needed in order to determine the shape of

[1] Although the MSEL is not specifically a tool for assessing posture development, the Gross Motor subscale includes items such as the ability to sit, stand, and squat.

change in posture development over time and whether it may differ between subgroups of HR and LR infants.

Finally, standardized examiner-administered measures such as the MSEL only provide information about whether or not an infant performs a behavior during the assessment window. Given that time spent engaging in an emergent behavior typically indexes the extent to which it is becoming well established (e.g., see Iverson and Thelen 1999), a more informative measure of postural skill development is how much time infants spend in various postures and ways in which these durations change over time. In addition, as noted above, unsupported sitting transforms infants' opportunities for interacting with objects and people. On a standardized assessment, infants may be credited with unsupported sitting because they can maintain balance for a brief period of time when placed in this posture. However, if they quickly topple over, or revert back to less demanding supported sitting or lying postures and do not actually spend time in this more challenging posture, they may not benefit in the same way as infants who can maintain balance in unsupported sitting for an extended period of time.

In the present study, we addressed these limitations in the following ways. First, we characterized trajectories of posture development in three subgroups of HR infants—HR-ASD, HR-Language Delay (LD), and HR-No Diagnosis (HR-ND)—and compared them to those of LR infants. This approach allowed us to examine the extent to which differences observed in the HR-ASD group may be specific to ASD or more generally characteristic of HR infants with other developmental concerns and to address the heterogeneity present among HR infants without ASD. Second, infant posture was densely sampled between the ages of 6 and 14 months, an age range that coincides with the emergence of new postures and increased mobility. By examining growth over time, we were able to go beyond simple comparisons of mean group differences and provide data on patterns of growth in posture skills among HR and LR infants. Finally, data were collected during in-home observations of HR and LR infants as they engaged in everyday activities. These observational data allowed us to examine longitudinal change in the amounts of time spent in various postures and infants' ability to sustain themselves in postures without caregiver support. Before infants can skillfully maintain unsupported postures (i.e., sitting and standing with arms free), they practice sustaining themselves using their arms and hands for support. Given the postural control difficulties observed in children and adults with ASD (Fournier et al. 2010), it is possible that HR infants are less likely than LR infants to sustain themselves while sitting or standing.

Methods

Participants

The present study included two groups of infants drawn from two separate longitudinal studies of early motor and language development. The first group included 59 (29 males) infants at heightened biological risk for an ASD diagnosis due to having an older sibling diagnosed with Autistic Disorder (HR infants; e.g., Ozonoff et al. 2011) verified prior to enrollment in the study using DSM-IV-TR criteria (American Psychiatric Association 2000) and scores above the Autism threshold on the Autism Diagnostic Observation Schedule-Generic (ADOS-G; Lord et al. 2000). Families of HR infants were recruited through a university Autism Research Program, parent support organizations, and local agencies and schools serving families of children with ASD. The second was a comparison group of 25 infants (10 male) with no family history of ASD (i.e., no first- or second-degree relatives with an ASD; Low Risk; LR) who participated in a separate longitudinal study (e.g., Iverson et al. 2007). Nine of these infants were first born and 16 had at least one older TD sibling. None of the older siblings of LR infants were diagnosed with ASD prior to or during the research study.

Infants in both groups were from English-speaking households and were from full term, uncomplicated pregnancies. Given that there is some evidence of difference in gross motor development based on socioeconomic status (SES; e.g., Capute et al. 1985), Nakao–Treas occupational prestige scores (Nakao and Treas, 1994) were calculated for fathers' occupation in order to provide an index of SES. Because many of the mothers were home raising their children, occupational prestige scores were calculated for fathers' occupation only. Table 1 displays demographic information for HR and LR participants in the study. As can be seen in the table, only one variable differed significantly between groups. At infant enrollment, fathers of HR infants were significantly older than fathers of LR infants (with statistical significance set at $p < 0.05$) $t(82) = -2.75$, $p = 0.007$.

Procedure

Infants in both longitudinal studies were visited at home each month by one primary experimenter and several research assistants for approximately 45 min. All visits were video- and audio-recorded. Visits were scheduled to take place within 3 days of the monthly anniversary of the infant's birthday. HR infants were visited at home monthly from 5 to 14 months of age, with 18, 24, and 36 month

Table 1 Demographic information for low risk and high risk groups

	Low risk (n = 25)	High risk (n = 59)	*p* value
Sex			0.482
Female (%)	15 (60)	30 (51)	
Male (%)	10 (40)	29 (49)	
Racial or ethnic minority (%)	1 (4)	7 (12)	0.426
Mean age of mothers (SD)	31.92 (4.95)	34.08 (4.41)	0.051
Mean age of fathers (SD)	33.08 (4.08)	35.81 (4.19)	0.007
Maternal education			0.056
High school (%)	1 (4)	5 (8)	
Some college or college degree (%)	10 (40)	37 (63)	
Graduate or professional school (%)	14 (56)	17 (29)	
Paternal education			0.817
High school (%)	3 (12)	4 (7)	
Some college or college degree (%)	13 (52)	32 (54)	
Graduate or professional school (%)	9 (36)	21 (36)	
Mean paternal occupational prestige (SD)[a]	55.21 (14.41)	57.50 (16.20)	0.557

[a]Nakao-Treas occupational prestige score; not able to be calculated for 3 fathers in High Risk group and 2 fathers in Low Risk group

χ^2 calculations were computed for Sex, Racial Ethnic Minority, Maternal/Paternal Education

T-tests were performed for Mean Maternal/Paternal Age and Mean Paternal Occupational Prestige

follow-up visits that included administration of standardized assessments (e.g., MSEL; see below). Attrition in the larger longitudinal study of HR infants was 6%; only HR infants with 36-month outcome data were included in the sample for the present study.

LR infants were observed at 2-week intervals from 2 to 19 months. Data collected at the visits coinciding with the monthly anniversary of the child's birthday were included in this study for purposes of comparison. Although there was extensive overlap between protocols for the two longitudinal studies, the focus of the research involving LR infants was on typical development and thus observer-administered standardized assessments were not included. However, no developmental concerns were reported by caregivers or research staff, and none of these children received intervention services. Furthermore, all LR infants scored at or within the normal range (≥ 10th percentile) on the MacArthur-Bates Communicative Development Inventory (CDI; Fenson et al. 2002) administered monthly from 8 to 19 months. Attrition for this study was 0%. Data collection for both the LR and HR groups took place between 2002 and 2014.

The present study focused on data obtained during the 25-min naturalistic and semi-structured play segments from the monthly home observation sessions at 6, 8, 10, 12, and 14 months. In the naturalistic segment, parents were asked to continue their normal activities; no attempt was made to structure this portion of the session in any way (with the exception that parents were asked to keep the television off). Typically, infants played on the floor with available toys during this time. Following the naturalistic segment, infants and parents participated in a semi-structured free play with favorite toys in which parents were instructed to play with their infant as they normally would. Most visits occurred in the family's living rooms, which were typically furnished with sofas, chairs, and coffee tables. An assortment of toys of a variety of sizes was readily accessible to parents and infants. Parents remained in close proximity to their infants throughout the visits. For the vast majority of infants (86% HR, 92% LR), the parent who interacted with the infant was the same across all visits.

Outcome Classification

At each follow-up visit (18, 24, and 36 months), parents of HR infants completed the MacArthur-Bates Communicative Development Inventory (CDI; Fenson et al. 2002), and HR infants were administered the Mullen Scales of Early Learning (MSEL; Mullen 1995). At the 36-month visit, HR infants were evaluated and administered the ADOS-G by a research-reliable clinician who was naïve to all previous study data. Infants received a diagnosis of ASD if both of the following criteria were met: an ADOS score that met or exceeded revised algorithm cutoffs for ASD or AD and a clinical best estimate diagnosis of AD 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). Fourteen HR infants (10 male) were classified as ASD (HR-ASD).

Table 2 Mean standardized scores at 36 months for the HR outcome groups

	HR-ND ($N=28$)		HR-LD ($N=17$)		HR-ASD ($N=14$)	
	M	*SD*	*M*	*SD*	*M*	*SD*
MSEL Visual Reception T Score	58.14[a]	14.22	51.71[a]	15.10	29.70[b]	12.95
MSEL Fine Motor T Score	50.71[a]	14.06	42.59[a]	14.26	26.00[b]	7.30
MSEL Receptive Language T Score	54.75[a]	9.29	44.41[b]	7.96	27.30[c]	10.40
MSEL Expressive Language T Score	59.12[a]	8.53	48.94[b]	8.03	31.73[c]	10.78
ADOS Severity Index	1.65[a]	1.47	1.80[a]	1.15	6.62[b]	2.06

MSEL Mullen Scales of Early Learning, *ADOS* Autism Diagnostic Observation Schedule

All children received either Module 1 ($n=8$) or Module 2 ($n=46$) based on their expressive language level at the time of the assessment. Differing subscripts show significant differences between groups as indicated by pairwise comparisons using the Bonferroni correction (i.e. means sharing the same superscript are not significantly different from each other, while means sharing a different superscript are significantly different from one another)

HR infants were classified as language delayed (LD) if they did not receive an ASD diagnosis and either of the following criteria were met (Parladé and Iverson 2015; Iverson et al. 2018):

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 to or greater than 1.5 SDs below the mean at 36 months.

These criteria have been used previously to identify language delay in both HR and community samples (e.g., Gershkoff-Stowe et al. 1997; Heilmann et al. 2005; Ozonoff et al. 2010; Parladé and Iverson 2015; Robertson and Weismer 1999; Weismer and Evans 2002). Seventeen HR infants were classified as LD without ASD (9 male).

The remaining 28 HR infants (10 male) were classified as No Diagnosis (ND) because they did not meet any of the previously described criteria for ASD or LD.[2] Table 2 presents scores from the MSEL and the ADOS for each of the three HR outcome groups at 36 months.

In the course of the study, we documented any instances in which infants were referred for evaluation due concerns about development and all subsequent early intervention that was provided. The percentages of HR infants who received early intervention services were as follows: HR-ASD = 85%, HR-LD = 50%, and HR-ND = 29%. Types of services included speech and language therapy, occupational therapy, child development therapy, physical therapy, and feeding therapy. On average, each therapy was provided once weekly for 1 h. The average numbers of different services being received were as follows: HR-ASD: $M=2.36$, HR-LD: $M=1.63$, HR-LD: $M=1.75$.

Coding

Coding of infant posture during the 25-min observation was carried out by a team of coders naive to infants' group membership and outcome classification using The Observer (The Observer Video-Pro version XT, Noldus Information Technology 2000), a video-linked computer program. Prior to initiation of coding, coders were trained to a minimum criterion of 80% agreement on three consecutive videos for all variables.

Infant posture was coded continuously using procedures adapted from Nickel et al. (2013). Onset and offset times for each posture were identified, and only postures sustained for at least 1 s were coded. Postures were further classified according to posture type (e.g., Lying, Supported Sitting, Unsupported Standing). A brief definition of each posture is presented in Table 3.

Supported Sitting and Supported Standing postures were further categorized on the basis of the source of support. *Infant Sustainment* involved the infant using his or her own body or hands for support with no contact from the caregiver (e.g., sitting in a tripod position with hands on the floor; leaning against a couch while standing). *Caregiver Sustainment* involved active and firm support from the caregiver.

[2] One HR-ND infant demonstrated nonspecific developmental delays ("other delay") as indicated by MSEL standard scores at or below 1.5 SD from the mean on the non-language subscales of the Mullen (i.e., Visual Reception, Fine Motor) at 36 months. This infant's parents did not report any concerns about her development, and she never received early intervention services. Further, visual inspection of the data suggested that posture development for this infant was not substantially different from other HR-ND infants; thus, the decision was made to retain this infant in this category.

Table 3 Definitions of posture types

Posture	Definition
Lying	
Lying	Lying on the stomach or on the back
Sitting	
Supported Sitting	Seated with support from the caregiver, hands, or body (e.g., sitting on couch and receiving back support from the couch)
Unsupported Sitting	Seated without support from the caregiver, hands, or body
All-four	
All-4	On hands and knees
Standing	
Supported Standing	Standing with support from the caregiver, hands, or body (e.g., leaning against the wall for support)
Unsupported Standing	Standing without support from caregiver, hands, or body

Reliability

Interrater reliability was assessed via independent coding of 22% (n = 84) of the video clips. Reliability videos were chosen so as to include participants from both groups and at all 5 age points. For posture identification, mean percent agreement averaged across the 84 videos was 86.8% (range: 77.5–97.8%). Mean Cohen's Kappa statistic for classification of sustainment type (infant vs. caregiver) was 0.89 (range: 0.80–0.96).

Data Reduction and Analysis

This study was designed to examine trajectories of posture development from 6 to 14 months in HR and LR infants. As previously discussed, the study procedure consisted of naturalistic observation and semistructured play, with a total of 25 min of observation coded for each participant. Although mean session lengths were highly similar and not significantly different across outcome groups (LR: $M = 24.70$, $SD = 1.64$; HR-ND: $M = 24.35$, $SD = 2.43$; HR-LD: $M = 24.46$, $SD = 2.43$; HR-ASD: $M = 25.00$, $SD = 0.57$), they varied slightly among participants. All duration variables were converted to percentages by dividing the total amount of time spent in a specific posture by the length of the observation.[3] Because of missing visits (e.g., infant not yet enrolled in study; visit missed due to illness or other unanticipated family events; unusable video) and/or malfunction of equipment, 6-month data were available for n = 69 (82%), 8-month data for n = 74 (88%), 10-month data for n = 81 (96%), 12 month data for n = 81 (96%), and 14 month data for n = 82 (98%) infants.[4]

Analytic Approach

Hierarchical Linear Modeling (HLM; Raudenbush and Bryk 2002) was utilized to describe differences in growth trajectories of early posture development based on infant risk status and outcome classification (LR, HR-ND, HR-LD, and HR-ASD). HLM is an appropriate analytical tool for data consisting of multiple time points nested within individuals and can assess data at two levels. First, HLM assess variation *within individuals* over time (i.e., growth trajectories; Level 1), and second, it assesses variation *between individuals* in growth trajectories (Level 2). HLM can accommodate unequally spaced data collection occasions, different data collection schedules, and missing data (Huttenlocher et al. 1991; Singer 1998; Willett et al. 1998). Thus, multilevel models both accommodate nested, hierarchical data and take appropriate advantage of all observations, resulting in greater power for the detection of effects (Raudenbush and Bryk 2002; Singer and Willett 2003).

All models were estimated in HLM 6.08 using Full Information Maximum Likelihood estimation (FIML; Raudenbush et al. 2010). For each variable, the process began with running a fully unconditional linear growth model with AGE (in months) as a predictor at Level-1 and with no

[3] Before conducting analyses all percentage data were arcsine transformed (2 × arcsin[sqrt(x)]) to correct for nonnormality that typically results from percentage data (Cohen et al., 2013). Models were run with both the arcsine transformed and non-transformed data. In all cases, normality improved with the arcsine transformation but results remained unchanged (although significance values may have attenuated or strengthened). Thus, for ease of interpretation, descriptive data (e.g., mean percentages) as well as the coefficients and standard errors for the HLM models reported below are those for the *untransformed* percentages.

[4] There were 15 missing sessions at 6 months (14 HR, 1 LR); 10 missing sessions at 8 months (9 HR, 1 LR); 3 missing sessions at 10 months (2 HR, 1 LR); 2 missing sessions at 12 months (1 HR, 1 LR); and 2 missing sessions at 14 months (both HR).

predictors at Level-2. In order to determine the most appropriate model of individual change, a quadratic model was run next by including AGE^2, and finally a cubic model was run by including AGE^3. Separate Chi square tests were used to test the change in deviance from the linear to the quadratic model and from the quadratic to the cubic model. Test significance represents a significant reduction in deviance from one model to the next, which generally indicates that the model with more parameters is a better fit for the data. Visual examination of individual infant posture growth trajectories was also useful in determining the most appropriate model of individual change (i.e., linear, quadratic, cubic; Raudenbush and Bryk 2002) for each dependent variable. Of the 8 dependent variables, a quadratic model was a better fit for the data in 7 cases and a linear growth model was the best fit in only one case (Infant Sustained Supported Sitting).

At Level 1 (within-person) of our final conditional models, HLM estimated individual growth trajectories in posture variables from 6 to 14 months as a function of age. AGE was measured in months and was always centered at the initial data collection point (i.e., 6 months). The quadratic (AGE^2) variable was calculated by squaring the centered linear age variable. The Level 1 model for a quadratic growth model is shown in Eq. 1.

$$Y_{it} = \pi_{0i} + \pi_{1i}(AGE_{it}) + \pi_{2i}\left(AGE_{it}^2\right) + e_{it} \quad (1)$$

where π_{0i} represents the intercept for infant i at the centered time point (i.e., 6 months), π_{1i} represents the instantaneous linear growth rate at the centered time point (i.e., rate and direction of growth at the point of the intercept), and π_{2i} represents the quadratic growth (i.e., acceleration or deceleration). In a quadratic model, instantaneous linear growth changes systematically over time depending on the rate of acceleration or deceleration. Thus, while the quadratic term is independent of time, both the intercept and the instantaneous linear growth depend on the point of intercept. Coefficients on the growth terms were modeled as random effects in all models.

At Level 2 (between individuals), outcome group (HR-ND, HR-LD, HR-ASD) and sex[5] (SEX) were included. These variables are considered time invariant predictors because they remained constant across observations for a given infant. The LR group was used as the comparison group, so analyses at Level 2 examined differences in growth trajectories between LR infants and the three outcome groups of HR infants controlling for sex. The Level 2 models for a quadratic growth model are shown in Eqs. 2–4:

$$\pi_{0i} = \beta_{0LR} + \beta_{01}\left(GEN_i\right) + \beta_{0HRND}\left(HRND_i\right) + \beta_{0LD}\left(HRLD_i\right) + \beta_{0ASD}\left(HRASD_i\right) + r_{0i} \quad (2)$$

$$\pi_{1i} = \beta_{1LR} + \beta_{11}\left(GEN_i\right) + \beta_{1HRND}\left(HRND_i\right) + \beta_{1LD}\left(HRLD_i\right) + \beta_{1ASD}\left(HRASD_i\right) + r_{1i} \quad (3)$$

$$\pi_{2i} = \beta_{2LR} + \beta_{21}\left(GEN_i\right) + \beta_{2HRND}\left(HRND_i\right) + \beta_{2LD}\left(HRLD_i\right) + \beta_{2ASD}\left(HRASD_i\right) + r_{2i} \quad (4)$$

where variation in the intercept (π_{0i}), instantaneous linear growth (π_{1i}), and quadratic growth (π_{2i}) are modeled as a function of four time-invariant infant characteristics. Thus, the coefficients (β) represent deviations from the LR group on each of these terms. For example, β_{1ASD} represents the deviation of the HR-ASD from the LR group in instantaneous linear growth.

Assumptions underlying statistical models were checked by assessing normality and homoscedasticity. Assumptions underlying statistical models were checked by assessing normality and homoscedasticity. In the few cases where outliers were identified, these values were removed, and models were fitted again; results remained unchanged. Therefore, the final models included all participants in the study with available data (i.e., no outliers were removed). Due to modest violations of assumptions, robust standard errors (which enable computation of sensible confidence intervals and tests even when residuals are not normally distributed; Raudenbush and Bryk 2002) are reported throughout.

For each analysis reported below, planned comparisons were performed by re-centering the AGE variable so that the trajectories' intercept systematically varied with age. This improved interpretability of the growth trajectories by allowing us to determine points at which developmental trajectories of different outcome groups either diverged or converged. Further analyses addressed specificity by rotating the reference group to examine potential differences between the HR-ASD and the other HR groups (HR-ND and HR-LD). These are reported in the description of results with the relevant p-values.

Results

Posture Duration

Our initial set of analyses modeled developmental trajectories of the amounts of time infants spent in six broad posture categories: Lying, Supported Sitting, Unsupported Sitting, All-4, Supported Standing, and Unsupported Standing from 6 and 14 months of age. Results are presented in the order

[5] Sex was included as a grand-mean centered covariate at Level 2 in light of evidence that boys may show a slight advantage over girls in gross motor performance (Thomas and French 1985).

Table 4 Mean percentage (M), standard deviations (SD), and ranges of posture durations

	LR			HR-ND			HR-LD			HR-ASD		
	M	*SD*	Range	*M*	*SD*	Range	*M*	*SD*	Range	*M*	*SD*	Range
6 months												
Lying	0.40	0.32	0.98	0.37	0.23	0.86	0.39	0.34	1.00	0.42	0.27	0.84
Supported Sit	0.26	0.23	0.91	0.35	0.23	0.93	0.44	0.29	0.81	0.46	0.20	0.66
Infant Sustained	0.31	0.38	1.00	0.24	0.28	0.86	0.23	0.29	0.94	0.07	0.08	0.19
Unsupported Sit	0.23	0.31	0.95	0.13	0.22	0.80	0.10	0.23	0.82	0.00	0.01	0.02
All-4	0.02	0.05	0.22	0.04	0.09	0.37	0.00	0.01	0.05	0.00	0.01	0.02
Supported Stand	0.06	0.11	0.36	0.06	0.06	0.21	0.03	0.03	0.10	0.02	0.04	0.09
Infant Sustained	0.13	0.31	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Unsupported Stand	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8 months												
Lying	0.09	0.15	0.60	0.13	0.21	0.98	0.18	0.19	0.65	0.18	0.28	0.88
Supported Sit	0.17	0.15	0.65	0.19	0.13	0.55	0.24	0.19	0.64	0.35	0.24	0.64
Infant Sustained	0.57	0.35	1.00	0.52	0.38	1.00	0.47	0.30	1.00	0.19	0.23	0.57
Unsupported Sit	0.45	0.27	0.86	0.40	0.27	0.94	0.41	0.28	0.96	0.39	0.29	0.78
All-4	0.12	0.12	0.36	0.15	0.16	0.54	0.07	0.09	0.25	0.04	0.08	0.23
Supported Stand	0.16	0.17	0.60	0.10	0.11	0.48	0.08	0.13	0.47	0.04	0.04	0.11
Infant Sustained	0.42	0.42	1.00	0.26	0.38	0.98	0.12	0.29	0.97	0.00	0.00	0.00
Unsupported Stand	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10 months												
Lying	0.02	0.04	0.20	0.04	0.08	0.37	0.02	0.03	0.13	0.15	0.26	0.87
Supported Sit	0.16	0.09	0.41	0.14	0.07	0.24	0.19	0.11	0.41	0.16	0.11	0.40
Infant Sustained	0.72	0.28	1.00	0.65	0.33	1.00	0.67	0.26	0.80	0.64	0.34	1.00
Unsupported Sit	0.33	0.18	0.71	0.46	0.21	0.80	0.51	0.19	0.73	0.47	0.24	0.93
All-4	0.14	0.10	0.41	0.11	0.10	0.38	0.15	0.09	0.30	0.11	0.08	0.29
Supported Stand	0.26	0.17	0.62	0.18	0.19	0.53	0.12	0.11	0.36	0.08	0.08	0.28
Infant Sustained	0.68	0.35	1.00	0.70	0.28	1.00	0.56	0.33	0.98	0.53	0.32	0.96
Unsupported Stand	0.02	0.06	0.22	0.02	0.05	0.27	0.01	0.02	0.07	0.00	0.00	0.01
12 months												
Lying	0.02	0.02	0.10	0.02	0.02	0.10	0.02	0.03	0.10	0.05	0.07	0.26
Supported Sit	0.19	0.16	0.53	0.16	0.10	0.37	0.21	0.12	0.49	0.20	0.10	0.40
Infant Sustained	0.64	0.34	0.96	0.68	0.31	0.95	0.61	0.35	0.98	0.62	0.31	0.96
Unsupported Sit	0.28	0.17	0.57	0.40	0.26	0.95	0.33	0.18	0.63	0.37	0.19	0.61
All-4	0.08	0.05	0.18	0.08	0.08	0.28	0.09	0.06	0.22	0.08	0.08	0.31
Supported Stand	0.23	0.21	0.82	0.18	0.18	0.63	0.18	0.13	0.52	0.15	0.13	0.46
Infant Sustained	0.64	0.35	1.00	0.73	0.33	1.00	0.74	0.29	1.00	0.48	0.41	0.96
Unsupported Stand	0.10	0.13	0.46	0.10	0.13	0.45	0.07	0.13	0.38	0.08	0.13	0.44
14 months												
Lying	0.02	0.02	0.06	0.02	0.02	0.08	0.03	0.05	0.16	0.03	0.05	0.14
Supported Sit	0.14	0.10	0.38	0.14	0.09	0.37	0.20	0.12	0.46	0.18	0.10	0.31
Infant Sustained	0.25	0.16	0.63	0.27	0.18	0.75	0.29	0.18	0.66	0.36	0.15	0.57
Unsupported Sit	0.69	0.32	0.94	0.72	0.26	0.87	0.77	0.26	0.88	0.72	0.28	0.89
All-4	0.04	0.04	0.17	0.08	0.09	0.41	0.06	0.06	0.23	0.12	0.05	0.17
Supported stand	0.23	0.12	0.51	0.17	0.12	0.45	0.13	0.07	0.25	0.12	0.08	0.23
Infant Sustained	0.90	0.12	0.41	0.77	0.28	1.00	0.72	0.27	0.99	0.80	0.19	0.60
Unsupported Stand	0.25	0.15	0.57	0.22	0.20	0.73	0.17	0.14	0.40	0.10	0.10	0.28

Table 5 Final models predicting growth trajectories for all postures with sex and outcome group

	Lying		Sit Supported		Sit Unsupported		All-4		Stand Supported[a]		Stand Unsupported[b]	
	Coefficient	SE	Coefficient	SE	Coefficient	SE	Coefficient	SE	Coefficient	SE	Coefficient	SE
Intercept												
Intercept β_{00}	0.364***	0.054	0.243***	0.042	0.282***	0.056	0.029*	0.013	0.039***	0.010		
Sex β_{01}	−0.082	0.063	0.011	0.051	0.067	0.057	0.004	0.015				
HR-ND β_{0HRND}	−0.031	0.071	0.089	0.057	−0.123	0.073	0.034	0.022				
HR-LD β_{0HRLD}	0.024	0.095	0.175*	0.081	−0.154*	0.081	−0.026	0.015				
HR-ASD β_{0HRASD}	0.022	0.105	0.214*	0.087	−0.225**	0.071	−0.021	0.016				
Linear growth												
Intercept β_{10}	−0.138***	0.022	−0.026	0.018	0.049	0.025	0.052***	0.009	0.079***	0.017	−0.019**	0.006
Sex β_{11}	0.030	0.025	−0.010	0.021	−0.057*	0.026	0.020*	0.009	0.006	0.015	0.002	0.007
HR-ND β_{1HRND}	0.028	0.030	−0.046	0.026	0.090*	0.037	−0.020	0.013	−0.032	0.022	0.003	0.009
HR-LD β_{1HRLD}	0.006	0.038	−0.060	0.031	0.106**	0.036	0.001	0.011	−0.048*	0.021	0.003	0.009
HR-ASD β_{1HRASD}	0.048	0.043	−0.065*	0.029	0.120***	0.035	−0.031**	0.011	−0.065**	0.020	0.013	0.008
Quadratic growth												
Intercept β_{20}	0.012***	0.002	0.002	0.002	−0.007*	0.003	−0.006***	0.001	−0.007**	0.002	0.006***	0.001
Sex β_{21}	−0.002	0.002	0.001	0.002	0.006*	0.003	−0.003*	0.001	−0.001	0.002	−0.001	0.001
HR-ND β_{2HRND}	−0.003	0.003	0.004	0.003	−0.009*	0.004	0.003	0.002	0.003	0.003	−0.001	0.002
HR-LD β_{2HRLD}	−0.001	0.004	0.006	0.003	−0.010*	0.004	0.001	0.001	0.005	0.003	−0.002	0.001
HR-ASD β_{2HRASD}	−0.006	0.004	0.005*	0.003	−0.010*	0.004	0.006***	0.002	0.007***	0.003	−0.004**	0.001

[a]The intercept term was fixed and did not include Level 2 predictors because of non-significant variation between infants

[b]The intercept was removed resulting in it being fixed at zero because it was not significantly different from zero

*$p<0.05$; **$p<0.01$; ***$p<0.001$

of the least developmentally advanced (Lying) to the most developmentally advanced posture type (Standing). Descriptive data are presented in Table 4 and the final model summaries are presented in Table 5.

During the model building process, results from the unconditional model indicated that the intercept term for Supported Standing did not vary significantly between infants. Therefore, the final conditional model included a fixed intercept term and did not include Level 2 predictors on the intercept (see Table 5). Similarly, the intercept term for Unsupported Standing did not vary significantly between infants and was not significantly different from zero. In this case, the intercept term was removed from the final conditional model resulting in it being fixed at zero. This was not surprising given that infants are typically not standing at 6 months of age.

Lying

Estimated growth trajectories for Lying from 6 to 14 months are presented for each of the four outcome groups in Fig. 1.

While the LR group spent approximately 36% of the time in Lying at 6 months, this declined rapidly, such that by 10 months they were no longer observed in Lying, with the trajectory remaining flat and stable from 10 to 14 months. The development of Lying for the HR infants without a later diagnosis of ASD (HR-ND and HR-LD) was comparable to that for LR infants, as indicated by no significant differences on any of the parameters.

Although the HR-ASD group did not differ significantly from the LR group in intercept or growth rates, they continued to spend time in the Lying posture at later ages (i.e., 10 and 12 months). Analyses revealed that they spent a greater percentage of time in Lying than the LR, HR-ND, and HR-LD groups at 10 months ($p=0.005$, 0.011, 0.022, respectively) and the LR and HR-ND groups at 12 months ($p=0.007$, 0.045, respectively).

Supported Sitting

Figure 2 displays the estimated growth trajectories for Supported Sitting from 6 to 14 months (i.e., infant was supporting him/herself or being supported by a caregiver) for each of the participant groups.

LR infants started out at 6 months spending approximately 24% of the time in Supported Sitting and the trajectory remained flat and stable over time. The HR-ND group did not differ significantly from the LR group in intercept or growth rates, suggesting that the development of Supported Sitting is comparable for HR-ND and LR infants.

Fig. 1 Developmental trajectories of Lying by outcome group from 6 to 14 months of age

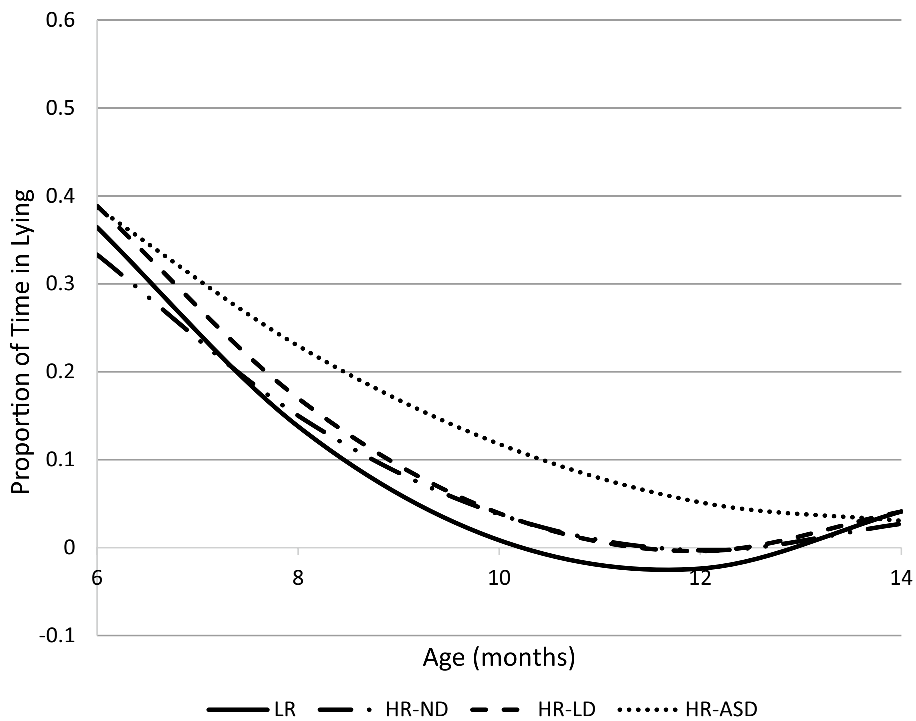
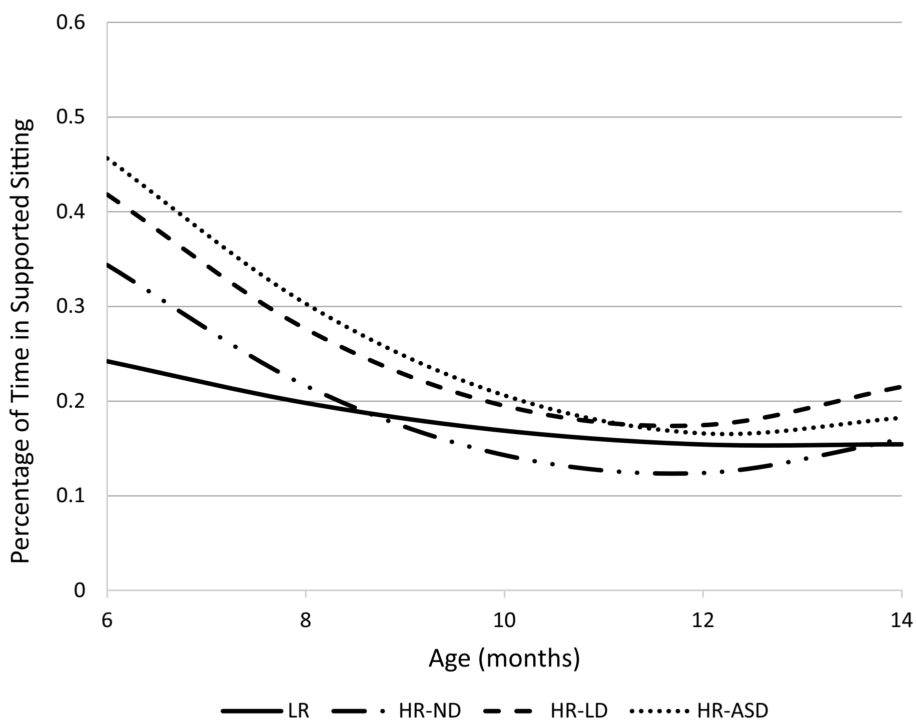


Fig. 2 Developmental trajectories of Supported Sitting by outcome group from 6 to 14 months of age



The HR-LD and HR-ASD groups displayed a different pattern of development in Supported Sitting. Specifically, HR-LD and HR-ASD infants started out at 6 months spending a significantly greater percentage of time in Supported Sitting than the LR group ($p = 0.035$, 0.016, respectively). From 6 to 10 months, both groups decreased relatively quickly in Supported Sitting, with the instantaneous linear growth rate differing significantly between

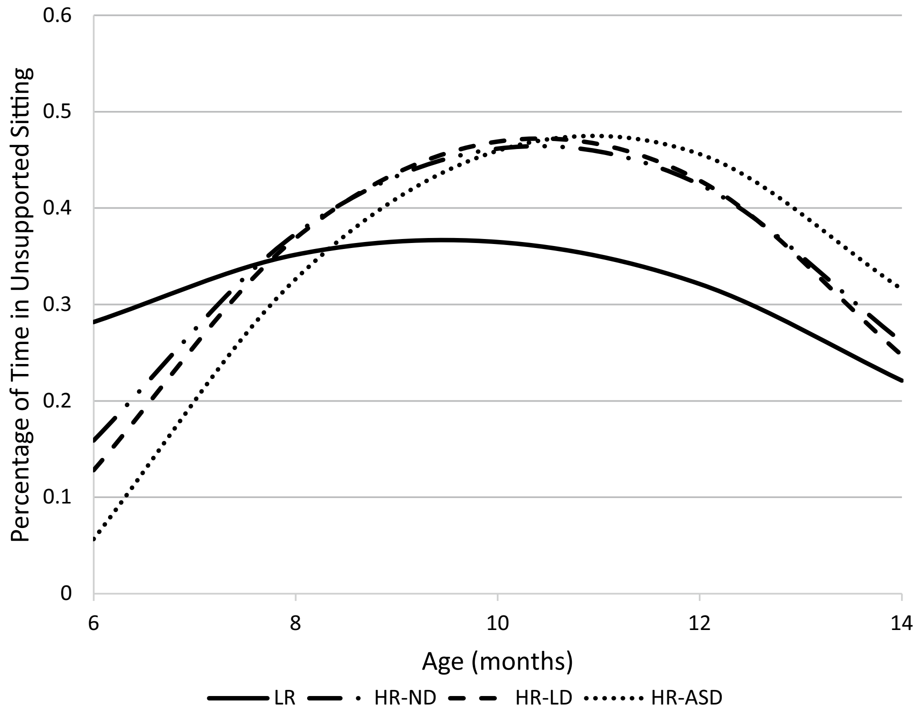


Fig. 3 Developmental trajectories of Unsupported Sitting by outcome group from 6 to 14 months of age

the LR and HR-ASD ($p = 0.028$) groups and marginally between the LR and HR-LD groups ($p = 0.058$).

Unsupported Sitting

Estimated growth trajectories for Unsupported Sitting (i.e., infant was seated without support from the hands, caregiver, or objects) from 6 to 14 months for each outcome classification group are presented in Fig. 3. Analyses of developmental change in the percent of time spent in Unsupported Sitting revealed that by 6 months, LR infants were already spending approximately 28% of the observation in Unsupported Sitting. Furthermore, they exhibited a relatively flat growth trajectory with slight deceleration (see Fig. 3).

As can be seen in Fig. 3, the three HR groups (HR-ND, HR-LD, and HR-ASD) displayed a different pattern of development in Unsupported Sitting. Relative to the LR group, the percentage of time spent in Unsupported Sitting at 6 months was lower for the three HR groups, although the difference was only significant for the HR-ASD ($p = 0.002$) and marginally significant for the HR-LD group ($p = 0.06$). In addition, compared to the LR group, all three HR groups (HR-ND, HR-LD, HR-ASD) displayed significantly faster instantaneous linear growth rates at the 6 month intercept ($p = 0.019$, 0.004, < 0.001, respectively) and greater deceleration over time ($p = 0.04$, 0.011, 0.017, respectively). This pattern of growth resulted in the HR-ND, HR-LD, and HR-ASD groups all spending greater percentages of time in Unsupported Sitting at 12 months than the LR group ($p = 0.033$, 0.011, 0.007, respectively). However, because of their greater decelerations, the HR groups decreased relatively quickly from 12 to 14 months, with all four groups exhibiting similar percentages of time in Unsupported Sitting at the final observation.

All-4

As can be seen in Fig. 4, which displays estimated growth trajectories for the All-4 posture from 6 to 14 months, LR infants spent approximately 3% of the time in All-4 at 6 months, increased the amount of time they spent in this position from 6 to 10 months, and then displayed a decrease between 10 and 14 months. The development of All-4 for the HR infants without a later diagnosis of ASD (HR-ND and HR-LD) was comparable to that for LR infants, as indicated by no significant differences on any model parameters.

The HR-ASD group had a significantly slower instantaneous linear growth rate at the 6 month intercept than the LR group ($p = 0.009$) and the HR-LD group ($p < 0.001$), indicating that the initial rate of growth in All-4 in infants who go on to have ASD is slowed. In addition, the HR-ASD group did not demonstrate the decelerating pattern characteristic of the LR group ($p < 0.001$) or the other two HR groups (HR-ND $p = 0.036$; HR-LD $p < 0.001$). Instead the HR-ASD group only demonstrated linear growth. As a result, the percentages of time spent in All-4 were lower for the HR-ASD group than the LR, HR-ND, and HR-LD groups at

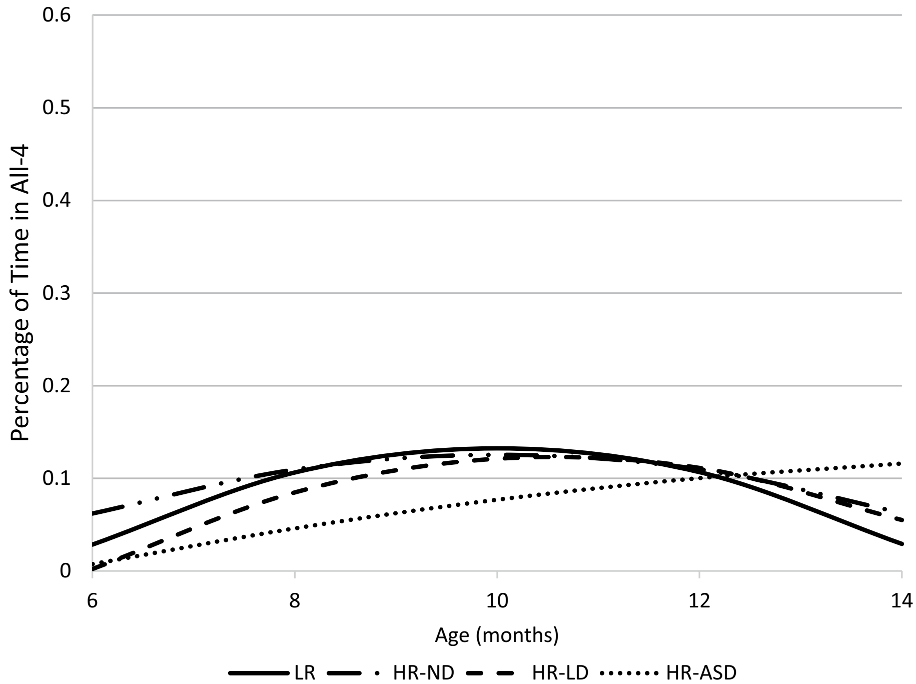


Fig. 4 Developmental trajectories of All-4 by outcome group from 6 to 14 months of age

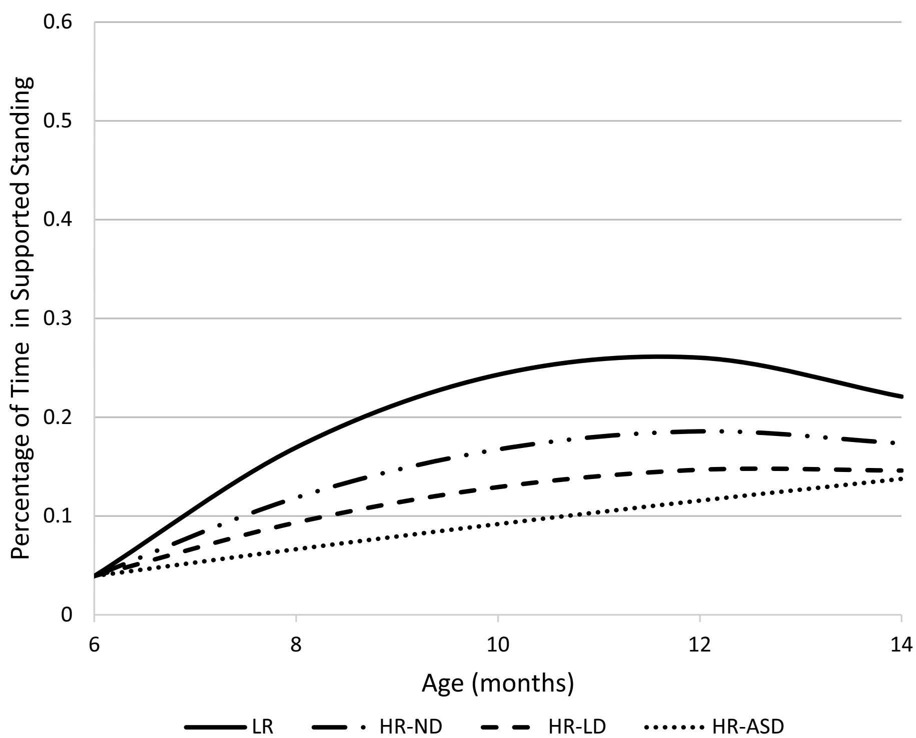


Fig. 5 Developmental trajectories of Supported Standing by outcome group from 6 to 14 months of age

both 8 ($p=0.002$; 0.006; 025, respectively) and 10 months ($p=0.009$; 0.038; 017, respectively). However, because of their linear pattern of growth, the HR-ASD group caught up to the other groups by 12 months, and by 14 months the percentage of time spent in All-4 by the HR-ASD group was significantly higher than that for the LR, HR-ND, and HR-LD groups ($p=0.001$; 0.023; 010, respectively).

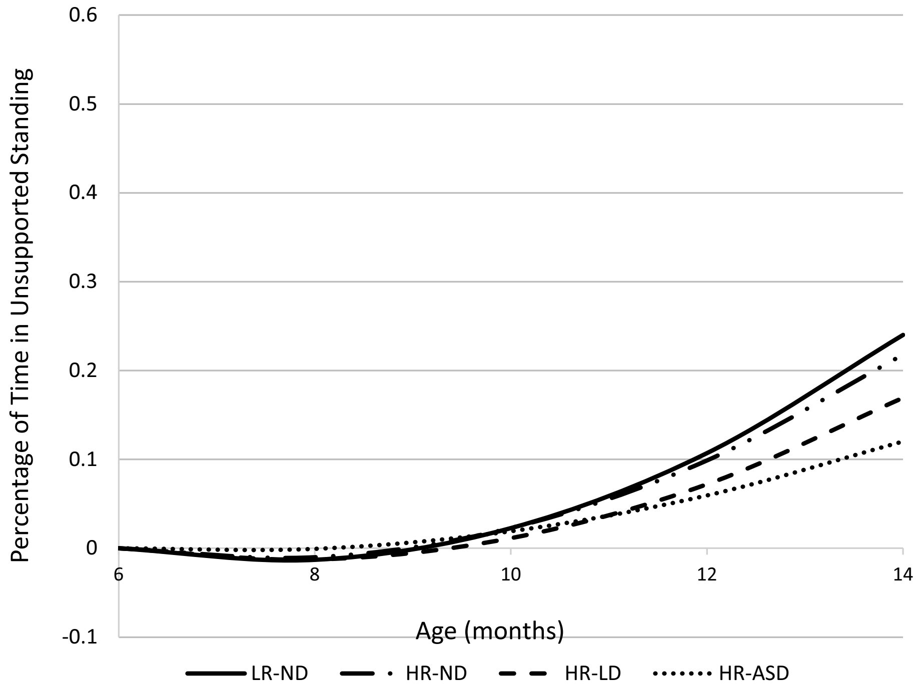


Fig. 6 Developmental trajectories of Unsupported Standing by outcome group from 6 to 14 months of age

Supported Standing

Estimated growth trajectories for Supported Standing (i.e., infant was standing supporting him/herself or being supported by a caregiver) from 6 to 14 months are presented in Fig. 5 for each of the four outcome groups.

As can be seen, the LR group started out spending approximately 4% of the session in Supported Standing. However, they increased relatively quickly, peaking at 10 months (26%), and then declining slightly by 14 months (22%). The HR-ND group displayed a similar, though attenuated, pattern of growth compared to the LR infants, but the two groups did not differ significantly from one another on any of the parameters.

Both the HR-LD and HR-ASD groups exhibited slower instantaneous linear growth rates at the 6 month intercept compared to the LR group ($p = 0.024$, 0.002, respectively). The HR-ASD group also did not demonstrate the decelerating pattern characteristic of the LR group and instead only exhibited linear growth ($p = 0.009$). The HR-LD and HR-ASD groups diverged from the LR group as early as 8 months ($p = 0.009$; $p < 0.001$, respectively) and this difference remained significant through 14 months ($p = 0.010$; 0.007, respectively).

Unsupported Standing

Figure 6 depicts the estimated growth trajectories for Unsupported Standing (i.e., infant was standing without support from the hands, caregiver, or objects) from 6 to 14 months for each of the outcome groups.

As is evident in the figure, it was estimated that the percentage of time in Unsupported Standing was very close to 0% from 6 to 10 months for all of the groups. The LR group demonstrated the fastest acceleration and by 14 months it was estimated that they were spending approximately 24% of the observation in the Unsupported Standing posture. The HR-ND group displayed a similar growth trajectory and did not differ from the LR infants on any parameter. While the HR-LD group exhibited slightly slower acceleration, they also did not differ significantly from the LR group.

By contrast, infants who were later diagnosed with ASD displayed significantly slower acceleration in the percentage of time spent in Unsupported Standing compared to the LR group ($p = 0.005$). The difference between the HR-ASD and LR group in the percentage of time spent in Unsupported Standing became significant by 14 months ($p = 0.006$). No significant differences were detected between the HR-ASD group and the HR-ND or HR-LD groups.

Infant Sustained Postures

The next set of analyses examined Infant Sustained Supported Sitting and standing postures. Before infants are able to sustain unsupported postures (i.e., unsupported sitting and standing with arms free) they practice holding themselves upright using their arms and hands for support. When infants attempt to sustain themselves in supported upright postures, they exhibit varied movement patterns which are important

Table 6 Final models predicting growth trajectories in Infant Sustained Sitting and Standing postures with sex and outcome group

	Infant Sustained Sit Supported		Infant Sustained[a] Stand Supported	
	Coefficient	SE	Coefficient	SE
Intercept				
Intercept β_{00}	0.435***	0.065		
Sex β_{01}	0.120	0.067		
HR-ND β_{0HRND}	−0.073	0.087		
HR-LD β_{0HRLD}	−0.123	0.089		
HR-ASD β_{0HRASD}	−0.294**	0.090		
Linear growth				
Intercept β_{10}	0.039**	0.012	0.203***	0.035
Sex β_{11}	−0.009	0.012	0.027	0.037
HR-ND β_{1HRND}	0.014	0.016	−0.012	0.046
HR-LD β_{1HRLD}	0.022	0.017	−0.047	0.045
HR-ASD β_{1HRASD}	0.040*	0.017	−0.147**	0.055
Quadratic growth				
Intercept β_{20}			−0.012**	0.004
Sex β_{21}			−0.002	0.005
HR-ND β_{2HRND}			0.001	0.006
HR-LD β_{2HRLD}			0.004	0.006
HR-ASD β_{2HRASD}			0.017*	0.007

[a]The intercept was removed resulting in it being fixed at zero because it was not significantly different from zero

*$p<0.05$; **$p<0.01$; ***$p<0.001$

for developing more complex postural control strategies that underlie the ability to skillfully maintain fully unsupported postures (Dusing and Harbourne 2010). In order to assess change over time in the developmental progression from supported to unsupported postures, we further classified Supported Sitting and Supported Standing postures as either Infant Sustained (i.e., an infant holding him or herself up using the hands or body but not receiving any support from the caregiver) or Caregiver Sustained. These variables were created by dividing the time spent in Infant Sustained Supported Sitting (or Supported Standing) by the total time spent in Supported Sitting (or Supported Standing). Because infant sustainment and caregiver sustainment durations sum to equal 100% of Supported Sitting and 100% of Supported Standing time, and because we were interested in examining change in infants' ability to support their own bodies in sitting and standing postures, we estimated growth trajectories for Infant Sustainment only. Descriptive data are presented in Table 4 and the final model summaries are presented in Table 6. As previously noted, the LR group served as the reference group in all analyses; therefore, the coefficients generated for HR-ASD, HR-LD, and HR-ND groups reflect deviations from the LR group in intercept, instantaneous linear growth, and/or quadratic growth.

Infant Sustained Supported Sitting

Figure 7 displays the estimated growth trajectories for Infant Sustained Supported Sitting from 6 to 14 months for each of the outcome groups. As previously mentioned, a linear growth model was the best fit for these data.

As can be seen, the LR group exhibited a pattern of positive linear growth in Infant Sustained Supported Sitting, steadily increasing from approximately 44% at 6 months to

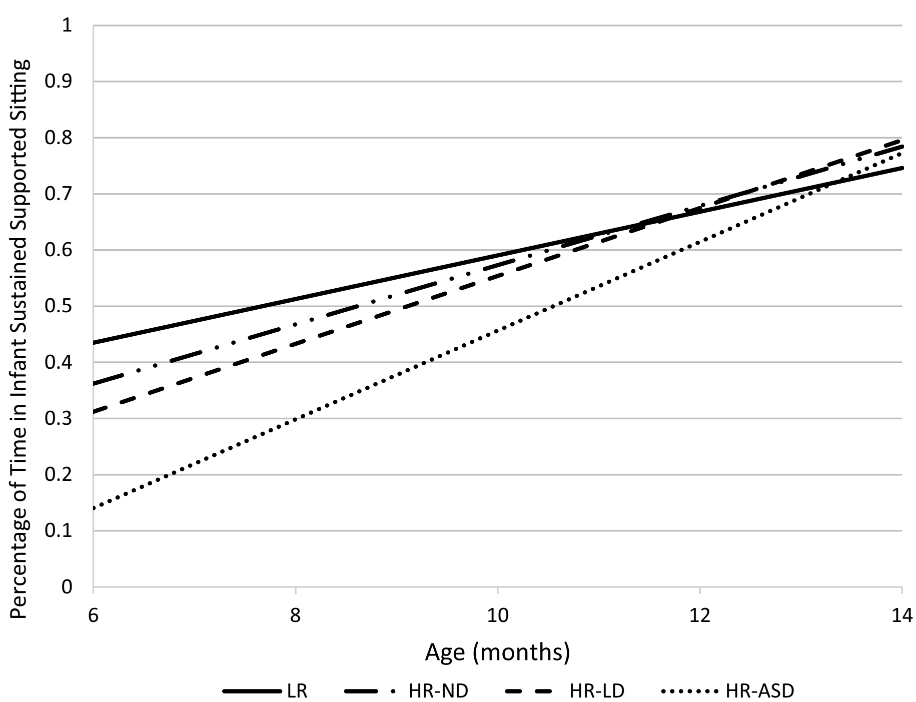


Fig. 7 Developmental trajectories of Infant Sustained Supported Sitting by outcome group from 6 to 14 months of age

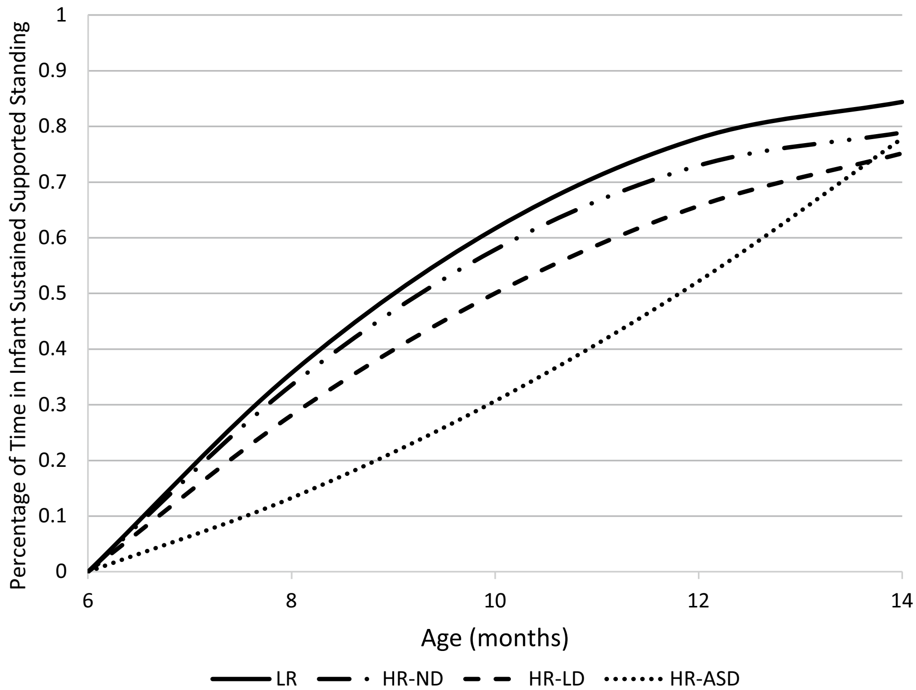


Fig. 8 Developmental trajectories of Infant Sustained Supported Standing by outcome group from 6 to 14 months of age

75% at 14 months. The HR-ND and HR-LD groups did not differ significantly from the LR group in 6 month intercept or growth rate, suggesting that the development of Infant Sustained Supported Sitting is comparable for HR infants without a later diagnosis of ASD and LR infants.

The HR-ASD group displayed a delayed developmental trajectory in Infant Sustained Supported Sitting. Specifically, the percentage of time in Infant Sustained Supported Sitting was significantly lower for the HR-ASD group than the LR group at 6 months ($p = 0.002$). However, the HR-ASD group increased twice as fast as the LR group ($p = 0.021$). While differences between the HR-ASD and LR groups remained significant at 8 ($p = 0.002$) and 10 months ($p = 0.017$), the HR-ASD group caught up to the LR group by 12 months due to their relatively fast growth rate.

The HR-ASD group also spent proportionately less time in Infant Sustained Supported Sitting at 6 and 8 months than the HR-ND ($p = 0.008$; 0.006) and HR-LD groups ($p = 0.049$; 0.032). At 10 months, the differences between the HR-ASD and HR-ND groups continued to be significant ($p = 0.024$).

Infant Sustained Supported Standing

Estimated growth trajectories for Infant Sustained Supported Standing from 6 to 14 months for each of the outcome groups are presented in Fig. 8. Because the intercept term for Infant Sustained Supported Standing did not vary significantly between infants and was not significantly different from zero, it was fixed at zero in the final conditional model (see Table 6).

As is evident in the figure, the LR group displayed a pattern of positive growth in Infant Sustained Supported Standing in which they increased relatively quickly early on and over time their rate of growth slowed. Analyses indicated that the HR-ND and HR-LD groups did not differ from the LR group on any parameter.

HR infants later diagnosed with ASD exhibited a delayed developmental trajectory. Specifically, the HR-ASD group had a significantly lower instantaneous linear growth rate at the 6 month intercept as compared to the LR ($p = 0.009$), HR-ND ($p = 0.011$), and HR-ASD groups ($p = 0.041$). As a result, the percentage of time spent in Infant Sustained Supported Standing from 8 to 12 months was lower for the HR-ASD group than the LR group ($p = 0.005$; 0.012; 024, respectively) and the HR-ND group ($p = 0.019$; 0.021; 0.031, respectively). However, because the HR-ASD group exhibited an accelerating growth trajectory rather than a decelerating trajectory like that of the other groups, they caught up to their peers by 14 months of age (see Fig. 8).

Discussion

The primary aim of the current study was to characterize trajectories of posture development across broad posture categories in three subgroups of HR infants (HR-ASD, HR-LD, HR-ND) and compare them to those of a group of LR infants. In addition, we were interested in determining whether HR and LR infants differed in their ability to self-support in Supported Sitting and Supported Standing postures (i.e., Infant Sustained postures).

The general pattern of results is consistent with the growing body of prospective research on motor development in infants eventually diagnosed with ASD suggesting that very early delays in posture development are among the earliest behavioral disruptions in the unfolding of the disorder (e.g., Estes et al. 2015; Flanagan et al. 2012; Leonard et al. 2013; Nickel et al. 2013). The present investigation also extends prior work by including a comparison HR-LD group, which permitted the identification of developmental patterns that may be specific to ASD. Our findings provide initial evidence that the infants who eventually received an ASD diagnosis, and to a lesser extent, those with non-ASD language delays, exhibited unique postural development trajectories that did not parallel those of infants with apparently neurotypical development. Furthermore, subtle differences in postural sustainment may help to differentiate infants eventually diagnosed with ASD from infants with non-ASD language delays. These findings are discussed in more detail below.

Posture Development in HR-ASD Infants is Characterized by Different Patterns of Growth Over Time

Development is a dynamic process in which abilities build upon and are nested within existing abilities (Thelen and Smith 1994). For example, pushing up on the hands and knees is nested within lying on the stomach in the prone position propped up on the arms. A unique aspect of the current study is that we examined multiple posture types longitudinally and at relatively frequent intervals, allowing us to observe developmental change in action and extend prior research that has collected data at more widely spaced time intervals (e.g., 6, 12, 18 months). Our findings revealed that HR-ASD infants followed an alternate route of development that reflected a slower transition from less advanced to more biomechanically challenging postures.

Specifically, while all groups decreased time spent in Lying and increased time spent in All-4 from 6 to 10 months, the HR-ASD group made this transition more slowly. As a result, by 10 months, relative to non-ASD infants, the HR-ASD group continued to spend a significantly greater percentage of time in the early emerging Lying posture and significantly less time in the more advanced All-4 posture. With regard to the development of the All-4 posture, the HR-ASD infants exhibited a different shape of change over time. Whereas all three comparison groups exhibited quadratic growth, in which there was an increase from 6 to 10 months followed by a decrease, the HR-ASD group exhibited only linear growth. In other words, the HR-ASD infants did not just exhibit a delay in All-4 (i.e., consistently less time in All-4 from 8 to 10 months); they exhibited a distinctive pattern of developmental change unlike that observed among HR and LR peers.

In a longitudinal study, Freedland and Bertenthal (1994) examined the transition from prone progression while lying on the belly to hands-and-knees crawling in the All-4 posture in TD infants. Their data suggest that the more erect posture depends on sufficient arm and leg strength to support the body in midair. Furthermore, the All-4 posture requires that the torso remain supported and balanced or the infant will topple over. Given that time spent performing an emergent behavior typically indexes the extent to which it is becoming well established (e.g., see Iverson and Thelen 1999), our findings suggest that the HR-ASD group may have lacked both sufficient strength and balance to effectively support themselves on hands and knees in All-4 and thus needed to revert to Lying postures even at the older 10-month age point.

We also observed a slower progression in the development of Unsupported Sitting and Standing in both the HR-ASD and HR-LD groups as compared to the LR group.[6] Specifically, by 6 months, the LR group had already transitioned to spending more time in Unsupported than Supported Sitting. In contrast, the HR infants spent more time in Supported than Unsupported sitting. By 8 months, the LR group had declined in time spent in Unsupported Sitting as they spent more time Standing. As a result, at 10 months, the HR-ASD and HR-LD groups spent more time than the LR group in Unsupported Sitting and less time than the LR group in Supported Standing. Furthermore, both the HR-ASD and HR-LD groups exhibited slower acceleration in Unsupported Standing compared to the LR group from 6 to 14 months, although this difference was only significant for the HR-ASD group.

Unsupported Sitting makes substantially new and different demands on infants' capacity to maintain balance in an upright posture. Specifically, infants must be able to control and coordinate their torsos from hips to shoulders and have sufficient strength in the neck muscles to hold their heads up in the face of ongoing postural sway. Flanagan et al. (2012) found that HR infants eventually diagnosed with ASD were more likely to exhibit head lag when pulled to a sit at 6 months than HR infants with no ASD symptoms. Thus, the delays that we observed in the current study in the progression to Unsupported Sitting may be directly related to delays or atypicalities in the development of head and trunk control among infant eventually diagnosed with ASD.

Additional demands on balance and strength are imposed by Unsupported Standing given the raised center of mass

[6] Although the HR-ND group exhibited a pattern of sitting development that was similar to the other HR groups, they did not differ significantly from the LR group on any growth parameters.

and the expansion of the locus of postural sway to the legs and feet. Although our data do not allow us to directly address questions of relative stability and control because they are limited to postural frequency and duration, the general pattern of results is consistent with previous research with older children and adults with ASD indicating greater postural instability and delays in the development of postural control compared to matched comparison individuals (e.g., Minshew et al. 2004). The results also support prior research with HR infants suggesting that a pattern of postural delays emerges relatively early in development among infants with ASD, well before then end of the first year of life and before other behavioral differences more specific to ASD are observable (Nickel et al. 2013).

Posture Development in HR-ASD infants is Characterized by Difficulty with Self Sustainment

There is substantial research on TD infants indicating that the skills required to flexibly and competently maintain unsupported postures (i.e., sitting and standing) consolidate relatively slowly and only after an extended period in which infants practice sustaining themselves using their arms and hands for support (e.g., see Adolph and Berger 2005). To characterize the developmental progression from supported to unsupported postures in HR infants, we further classified Supported Sitting and Supported Standing postures as either Infant or Caregiver Sustained.

From 6 to 14 months, all of the groups increased in infant sustainment. However, compared to all three non-ASD groups (LR, HR-ND, HR-LD), the HR-ASD infants exhibited slower growth in both Infant Sustained Sitting and Standing postures. Given that in the present study the reciprocal of infant sustainment was caregiver sustainment, it can be inferred that the HR-ASD infants were spending a proportionally greater amount of time in supported postures being sustained by a caregiver than non-ASD infants.

The variability in movement that is created when infants sustain themselves in supported upright postures provides important opportunities for infants to develop complex postural control strategies as they explore the boundaries within which they can remain stable (Dusing and Harbourne 2010). In contrast, sustainment by a caregiver may reduce opportunities for varied movements and result in infants getting stuck in simple and repetitive movement patterns (Dusing et al. 2009; Thelen 2004). Within Infant Sustained Supported Sitting and Standing, infants assume many different positions and frequently topple over when lifting their hands off a supporting surface to reach for objects and people in their environments. Practice with falling in a variety of situations provides opportunities for infants to learn that some strategies are not successful, which can lead to more adaptive control of motor actions (Adolph et al. 2012; Joh and Adolph 2006). Thus, decreased time in Infant Sustained Supported Sitting and Supported Standing may not only negatively affect the building of muscle strength and balance needed for Unsupported Sitting and Standing; it may also limit valuable experiences with exploring new and varied movement patterns.

Cascading Effects of Posture Development and Delay

Much of the first year and a half of life involves infants acting on and moving through their environments. Posture development is central to this given that all actions require a stable base of support (Adolph and Berger 2005). Moreover, the attainment of various postures creates the necessary conditions for infants to obtain broader and more diverse opportunities for engaging with people, objects, and even their own bodies, which in turn supports learning (Campos et al. 2000; Iverson 2010). There is growing evidence among neurotypical infants as well as infants with motor delays that early posture behavior relates to a wide range of domains, from perception to language (e.g., Karasik et al. 2011; Soska et al. 2010; Surkar et al. 2015; Walle and Campos 2014; Yingling 1981).

One implication of this framework is that early-emerging and even subtle motor disruptions have the potential to constrain other areas of development. To illustrate, consider the acquisition of sitting. As postural control improves and infants advance from Supported to Unsupported Sitting, they can gradually shift allocating resources from the initially challenging control of the sitting posture to the task of focused visual attention to objects (Surkar et al. 2015). Furthermore, once infants are able to sit unsupported, their trunks are stabilized so that their arms and heads are free to move, allowing them to reach for, grasp, and manipulate objects in new and increasingly sophisticated ways that involve the coupling between visual inspection and object exploration as well as bimanual manipulation (Soska et al. 2010).

As infants begin to show growing skill in object manipulation and focused attention to objects, caregivers increasingly help them acquire and manipulate objects, introduce new play routines with objects (e.g., Fogel 1990), and comment on the objects toward which infants are directing their gaze or reaching. This may support the development of joint attention, which involves the ability to shift eye gaze between the caregiver and an object—the first major milestone in social communicative development (e.g., Bakeman and Adamson 1984). It also affords opportunities for caregivers to provide valuable linguistic input (e.g., to name the object for which the infant is reaching) at just the optimal moment (when s/he is actively attending to the object) for word learning (e.g., Tomasello and Farrar 1986).

Unsupported Sitting, in other words, creates new conditions for object exploration, joint attention, and early communication, all of which are important for subsequent cognitive, perceptual, and language development.

Imagine, then, the consequences of a delay in the development of stable Unsupported Sitting. An infant who must continue to use hands for support will have restricted opportunities for object directed reaching. In addition, because of the attentional demands of maintaining balance and control in an unstable sitting posture, this infant will likely have fewer resources available for focusing on objects. A reduction in both reaching and focused attention to objects may lead to fewer opportunities for caregivers to scaffold emerging joint attention abilities and provide linguistic input linked to their infant's immediate focus of attention. Thus, one outcome of this cascade may be that the infant who is delayed in posture development may become a toddler delayed in the development of social communication and language.

The consequences of even minor motor disruptions for future development may be particularly far-reaching for infants with ASD, who are vulnerable to social communication impairments and often experience delays and/or deficits across a variety of domains. These motor disruptions may compound this vulnerability and further constrain communication development (Thelen 2004). However, conclusions regarding the causal nature of these relations are premature. Researchers are beginning to examine links between motor and communication development in infants at risk for ASD (Bradshaw et al. 2018; West et al. 2017), and continued research in this area will be important for understanding mechanisms of both typical and atypical development.[7] Furthermore, it is likely that motor and communicative behaviors, which have overlapping neural correlates, are disrupted as a result of atypical brain development in infants eventually diagnosed with ASD (e.g., Hazlett et al. 2017). However, this is not mutually exclusive with the developmental account proposed here. As West (2018) observed in a recent meta-analysis, "Even if motor and communication are both disrupted as a result of atypical neural development, it is still likely that the resulting atypical motor behavior will further influence infants' social and sensory experiences, compounding on vulnerability in social and communicative development in ASD." Understanding cascading effects of very early developmental delays provides important information regarding points for behavioral intervention.

Limitations

To our knowledge, this study provides the most detailed examination of posture development in HR infants with varying developmental outcomes to date. While the prospective longitudinal design and detailed micro-analytic coding of posture behavior in a naturalistic setting are strengths of this research, a note of caution regarding the interpretation of the findings is in order. First, our sample size, especially the HR-ASD group, was relatively small and consisted primarily of well-educated Caucasian families. Furthermore, researchers have noted that findings derived from the "baby siblings" who developed ASD may not be generalizable to individuals with ASD sampled from the general population given that family risk factor as well as the experience of living in a family with a child with ASD might have influenced development in some unknown way (Szatmari et al. 2016). Thus, results clearly merit replication with a larger and more diverse sample.

Second, although there were no parental or researcher concerns about development for any of the LR children, and the available CDI data and our subsequent contact with families of LR children gives us every confidence that these children were developing typically, the lack of standardized assessments (e.g., Mullen, ADOS) precludes us from stating with certainty that none of these children ever developed delays or ASD after 19 month of age. In addition, nine of the 25 LR infants were first born, which is a limitation given that family dynamics are different for children who are born first versus later. There were also more females in the LR group than the HR group. However, given that boys may show a slight advantage over girls in gross motor performance, sex was included as a covariate in the models (Thomas and French 1985).

Lastly, it may be important in future studies to gather more objective measures of the natural environment (e.g., size of the space, detailed description of furniture and toys, measures of caregiver proximity to the child during the interaction). In addition, coding different forms of infant locomotion (e.g., rolling, scooting, crawling, walking) is an important and interesting next step for future studies.

Clinical Implications

While delayed posture development may not be specific to infants eventually diagnosed with ASD (e.g., Ungerer and Sigman 1983; Van Haastert et al. 2006), given the importance of skilled movement for social communication, language, and cognition (Iverson 2010; Thelen 2004), identifying such delays and providing appropriate intervention at an early age is critical. The results reported here indicate the importance of considering broad patterns of delays in posture development, particularly during the first

[7] While motor development can be an agent of change for the developing language and communication system, the acquisition of language draws on a complex array of multiple skills from multiple domains. In addition, there are likely alternative pathways for accessing similar language learning contexts that, in normative development, are provided by gains in motor skills (Iverson 2010).

year, in infants at heightened risk for ASD. The majority of early screening measures for ASD focus on social-communicative behaviors that are not well established until the second year, even in typical development (e.g., Robins et al. 2001). Although it is not practical to code behavior frequencies and durations of posture behaviors during medical office visits, these results suggest that it may be possible to develop measures that can be rated by physicians or nursing staff during well-child visits to capture additional information about an infant's skills in this area.

Posture skills are developmentally appropriate and relatively straightforward targets for early intervention. Identifying and intervening with infants who have early motor delays may be particularly important because achievements in these domains transform infants' earliest experiences. While early intervention programs for infants exhibiting early signs of ASD should clearly focus on the core symptoms of the disorder (social engagement and reciprocity), it may also be useful, within these broader early intervention models, to consider ways in which improvements in postural stability can set the stage for enhancement of social communication and language development (see Bradshaw et al. 2015, for a review of very early interventions for ASD). Instead of focusing on improving motor abilities (e.g., muscle strength, balance, and range of motion) or social communication skills in isolation, it will likely be more effective to focus on broadly enhancing the infant's capacity for exploratory experiences while emphasizing the bidirectional influence of the infant and caregiver across time (Lobo et al. 2013). This idea is supported by research on the efficacy of the Early Start Denver Model, which takes a holistic and developmental approach to the treatment of very young children with ASD (Dawson et al. 2010).

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical Approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed Consent Informed consent was obtained for all individual participants in the study.

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