

Toy-oriented changes during early arm movements: Hand kinematics

A.N. Bhat, J.C. Galloway*

*Infant Motor Behavior Laboratory, Department of Physical Therapy, Biomechanics and Movement Science Program,
University of Delaware, Newark, DE 19716, USA*

Received 4 September 2005; received in revised form 17 January 2006; accepted 20 January 2006

Abstract

In a recent cross-sectional study, we found that young infants changed their spontaneous arm movements in the presence of a toy, termed ‘toy-oriented changes’, in systematic ways beginning many weeks before their first consistent reaches [Bhat, A. N., Heathcock, J. H., & Galloway, J. C. (2005). Toy-oriented changes in hand and joint kinematics during the emergence of purposeful reaching. *Infant Behavior and Development*, 28(4), 445–465]. The purpose of the present study was to test specific hypotheses regarding toy-oriented changes in a longitudinal design.

Methods: Thirteen infants were observed every other week from 8 weeks of age up to the onset of reaching. At each session, hand and joint motions were observed with and without a toy present using a high-speed motion capture system. This paper focuses on the toy-oriented changes in hand variables.

Results: As predicted, infants displayed a meaningful pattern of toy-oriented changes, which systematically changed as infants approached the first week of reaching. During the *Early phase* (8–10 weeks before reaching), infants scaled down their movement length and speed in the presence of a toy. During the *Mid phase* (4–6 weeks before reaching), infants scaled up movement number and speed, increased movement smoothness, and decreased their hand–toy distance in the presence of a toy. During the *Late phase* (within 2 weeks of reaching), infants continued to change their hand’s position to get closer to the toy and began contacting it. Interestingly, movement number and smoothness displayed similar developmental patterns, where movement length and speed displayed similar patterns.

Conclusion: Toy-oriented adaptation of arm movements emerges in the first months of life and forms a complex, yet tractable continuum with purposeful reaching. These results provide a foundation to test more specific hypotheses of hand and joint coordination in both typically developing infants and those infants born at risk for coordination impairments.

© 2006 Elsevier Inc. All rights reserved.

Keywords: Toy-oriented changes; Arm movement; Infants

1. Introduction

Infants reach for and contact objects between 3 and 5 months of age (Thelen et al., 1993; von Hofsten, 1991). In the months before reaching, infants move their arms multiple times per minute with or without a clear external stimulus (Piek & Carman, 1994; Thelen, 1979). Although early leg movements (Chen, Fetters, Holt, & Saltzmann,

* Corresponding author. Tel.: +1 302 831 3697; fax: +1 302 831 4234.
E-mail address: jacgallo@udel.edu (J.C. Galloway).

2002; Cioni, Ferrari, Einspieler, Paolicelli, & Barbani, 1997; Heriza, 1988a, 1988b; Piek, 1998; Piek & Carman, 1994; Thelen, 1979, 1985, 1994; Thelen & Fisher, 1983; Zelazo, Zelazo, & Kolb, 1972) and the broader category of early body movements (Hadders-Algra & Prechtl, 1992; Prechtl & Hopkins, 1986; Robertson, 1993; Robertson, Bacher, & Huntington, 2001) have been studied for some time, less is known about early arm movements (Piek & Carman, 1994; Spencer & Thelen, 2000; Spencer, Vereijken, Diedrich, & Thelen, 2000; Thelen et al., 1993; von Hofsten, 1982, 1984). Moreover, it is not clear when infants begin to adapt their early arm movements in the presence of a toy, which we term ‘toy-oriented changes’, how toy-oriented changes differ across the prereaching period, or the relationship of these toy-oriented changes to the emergence of purposeful reaching.

A detailed understanding of how purposeful reaching first emerges is of interest to developmental psychology, neuroscience and pediatric medicine for several reasons. First, early arm movements help shape and are, in turn, shaped by the cortical and subcortical areas that contribute to purposeful motor behaviors (Eyre, Miller, Clowry, Conway, & Watts, 2000; Eyre, Taylor, Villagra, Smith, & Miller, 2001; Martin, Choy, Pullman, & Meng, 2004; Martin, Engber, & Meng, 2005). Second, early arm movements have been proposed to provide the sensorimotor experiences by which infants learn the arm control required for purposeful reaching (Kawai, Savelsbergh, & Wimmers, 1999; Out, Savelsbergh, van Soest, & Hopkins, 1997; Out, van Soest, Savelsbergh, & Hopkins, 1998; Thelen et al., 1993; Turvey & Fitzpatrick, 1993; von Hofsten, 1993). Indeed, infants provided with opportunities to produce additional early arm movements contact toys earlier than controls (Lobo, Galloway, & Savelsbergh, 2004). Third, with the emergence of reaching, infants, for the first time, begin to independently explore and physically manipulate their environment. Thus, the emergence of reaching further influences motor (Corbetta & Bojczyk, 2002; Goldfield, 1990), social (Fogel, 1992; Fogel, Dedo, & McEwen, 1992), perceptual (Corbetta, Thelen, & Johnson, 2001; Eppler, 1995; Rochat, 1989), and cognitive development (Diedrich, Highlands, Spahr, Thelen, & Smith, 2001; Thelen, Schöner, Scheier, & Smith, 2001). Lastly, toy-oriented changes in early arm movements in typically developing infants provides the normative database for the early identification of movement impairments in infants born at risk of reaching delays such as those born preterm and with low birth weight (Fallang, Saugstad, Groggaard, & Hadders-Algra, 2003), with intrauterine drug exposure (Tronik, Fetters, Olson, & Chen, 2004), or with brachial plexus birth palsy (Gert van Dijk, Pondaag, & Malessy, 2001). Therefore, the purpose of the present study was to conduct a comprehensive longitudinal examination of toy-oriented changes in arm movements, that is, how infants changed their spontaneous arm movements in the presence of a toy.

The relatively few studies on early arm movements, either with or without a toy present, suggest that meaningful developmental changes may be occurring months before the onset of reaching. *Without a toy present*, infants decreased the number of arm movements in the months leading up to reach onset (Piek & Carman, 1994; Thelen, 1981) as they gradually increased the number of midline arm movements including hand to mouth and face behaviors (Galloway & Thelen, 2003; Lew & Butterworth, 1997). Changes in arm movements without a toy present have been proposed to be the foundation by which infants build toy-oriented changes in their movements including purposeful reaching (Galloway & Thelen, 2003). *With a toy present*, newborns increased the number of forward arm movements when looking at the toy (Bacher, 1998; von Hofsten, 1982). Older infants moved their arms more frequently (Galloway & Thelen, 2003; von Hofsten, 1984) and gradually closer to the toy over the weeks before reach onset compared to movements without a toy present (Galloway & Thelen, 2003; Spencer & Thelen, 2000). In general, spatial changes of hand variables appear relatively consistent across studies. In contrast, temporal changes in hand kinematics such as movement speed may be more complex and individualized. For example, although newly-reaching infants tend to reach within a relatively narrow range of speeds (Berthier, Clifton, McCall, & Robin, 1999), Thelen et al. (1993) found noted examples of infants slowing down as well as speeding up their early arm movements in the weeks leading up to reach onset.

In a recent cross-sectional study, we found that non-reaching, nearly-reaching and newly-reaching infants showed toy-oriented changes clustered into early, late, and non-linear features in the months up to the onset of reaching (Bhat, Heathcock, & Galloway, 2005). Specifically, the three groups of infants were differentiated by their toy-oriented changes in movement number, speed, length, and hand–toy distance. Moreover, toy-oriented changes occurring between 8 and 14 weeks of age appeared to differ from changes occurring between 14 and 19 weeks of age. Hence, in the present longitudinal study, we made several hypotheses. First, infants would display toy-oriented changes beginning many weeks before reaching. Second, the pattern of toy-oriented changes would differ across 8, 14, and 19 weeks. Third, certain toy-oriented changes would show continuity with the emergence of reaching whereas others would be specific to a particular developmental time period.

2. Materials and methods

2.1. Participants

Thirteen healthy, full-term infants (eight females and five males) were recruited from the Newark, Delaware community through public birth announcements. Infants visited the laboratory every other week from 8 weeks of age up to the week of reach onset (average week of reach onset 19.5 weeks of age \pm 2.4 weeks), defined as the first week that total toy contacts were three times greater than any previous week. Interestingly, this was not a difficult determination as infants averaged between 0 and 1.1 ± 2.1 contacts in the two sessions before reach onset and 41.7 ± 18.9 contacts on their week of reach onset. A single experimenter coded the toy contacts for all infants. Paired samples correlation on 572 contacts across 12 infants found very high intra-rater reliability ($r^2 = 0.975$) across two coding sessions. The total number of visits varied slightly between infants because the week of reach onset varied across infants, and there were a few missed sessions due to sickness or excessive crying (>2 min). Infants were admitted in the study following informed parental consent as approved by the University of Delaware Human Subjects Review Board.

2.2. Procedure

Infants were seated in a custom made chair, reclined at a 30° angle to the vertical. The design of the chair allowed free range of motion of the arms and legs (Fig. 1A). Across both experimental conditions, infants were typically alert and moving, but not fussy or crying. During the “no toy” condition, an experimenter was seated in front of the infant and spoke to the infant to maintain arousal and movement. During the “toy” condition, the same experimenter held a midline toy at the infant’s shoulder height, arm’s length and at the midpoint between both shoulders and spoke to the infant as in the ‘no toy’ condition. The order of experimental conditions (toy and no toy) was alternated between visits. An average of 6.4 ± 0.92 trials, 30 s long were recorded for each condition (Table 1).

2.3. Kinematic analysis

A six-camera (120 Hz) Vicon motion capture system was used to obtain position–time data from both arms (Vicon Motion Systems Inc., CA, USA). Cameras surrounded the infant chair in a semi-circular fashion with two cameras on each side and two in the front of the infant. Infants were seated within a calibrated volume of 160 cm \times 160 cm \times 200 cm. The average measurement error ranges between 0.2 and 0.3 mm for the given calibrated volume. An array of three reflective, non-linear markers (8 mm in diameter) was placed on the right and left dorsum of hand and on the toy. The calculations for hand kinematics were performed for the right arm only. For each trial, the 3D position for each marker was calculated and filtered at 4 Hz with a 4th order Butterworth filter. First, we calculated the 3D linear position of the hand. Next, we calculated the 3D resultant speed of hand using a three-point differentiation technique. The calculations for hand kinematics were performed through custom Matlab programming (Mathworks, Inc.). An average of 6 min of motion data (3.5 ± 0.62 min per condition) were recorded per infant per session. In addition, a loss of no more than 10 consecutive frames of marker position data (equal to 1/12th of a second) was interpolated using cubic spline interpolation. Following the interpolation, 99% of the recorded data per experimental condition per infant were used for further analysis. This matches or exceeds the amount of data used by similar studies (Konczak, Borutta, Topka, & Dichgans, 1995; Thelen et al., 1993; von Hofsten & Ronnqvist, 1993).

3. Data analysis

3.1. Movement identification

All dependent variables were analyzed per movement. A “movement” was operationally defined as 3D hand displacement ≥ 30 mm in length. A movement reversal of ≥ 15 mm denoted the end of the preceding movement and the start of the next movement (Fig. 1B and C). A custom Matlab program selected the movements and an experimenter visually confirmed each selection by observing the 3D hand position profile. Our goal was to capture all types of movements, small as well as large; hence, we used a threshold of 30 mm. This threshold length was chosen as it reflected the linear distance the hand moves with approximately 10° of motion of a single joint given a limb segment

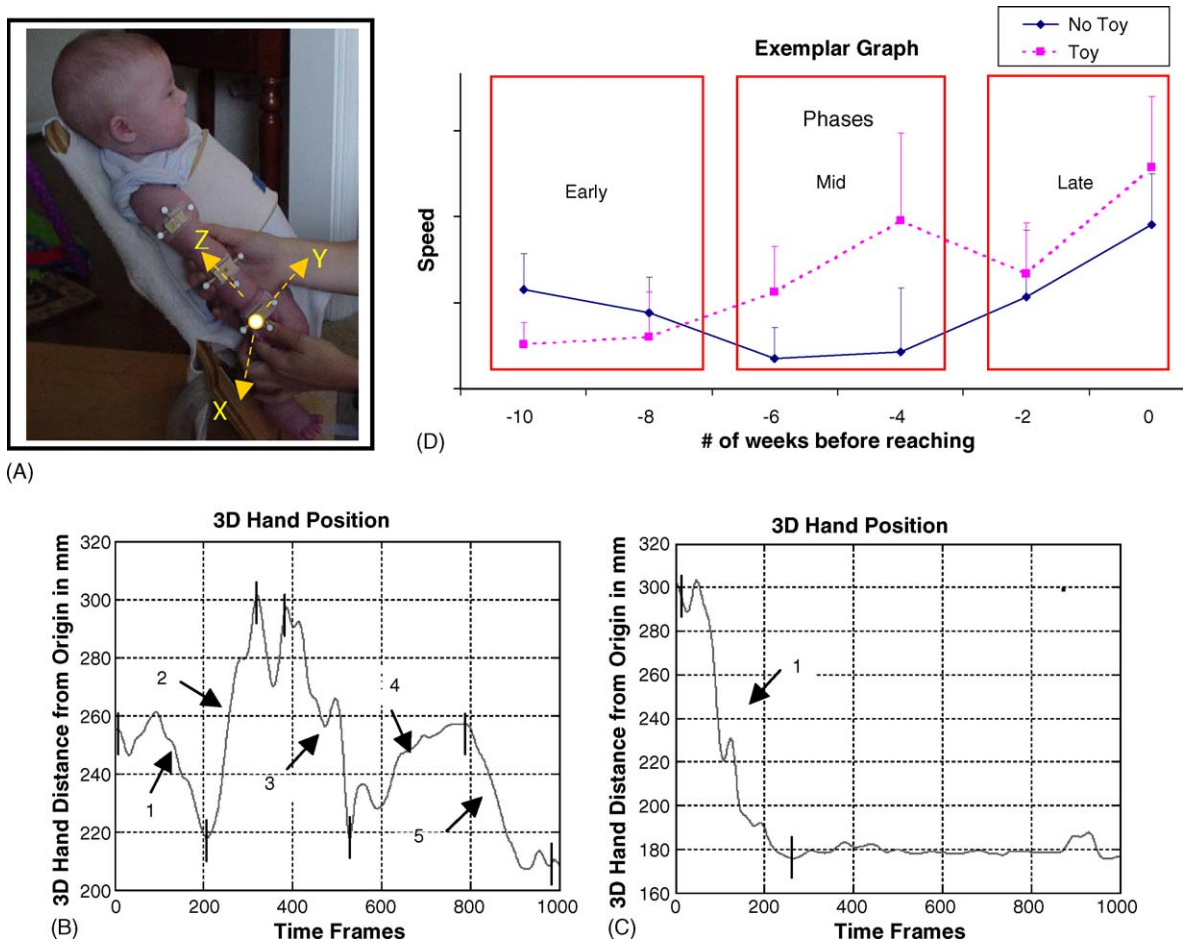


Fig. 1. An infant in the custom made chair and the orientation of the X-, Y-, and Z-axis of the coordinate system (A), movement identified within the profile of the 3D hand position (five movements in (B) and one movement in (C)), shows an exemplar graph of how the 6 weeks were divided into three phases: Early, Mid, and Late (D). Note the similar toy-oriented differences across adjacent weeks.

length of 20 cm, which was the average arm length of our infants. For each movement, multiple dependent variables were calculated, as described below.

4. Dependent variables

Movement number (movement per minute): The total number of hand movements normalized by the total duration of all trials per condition. **Number of velocity peaks:** The total number of peaks in the hand's 3D speed profile per movement. **Length of hand movement (mm):** The 3D distance between the start and end of a movement. **Speed of hand movement (mm/s):** The average 3D speed of hand motion per movement. **Minimum hand to toy distance (mm):** The minimum distance of the hand from the toy location at the end of movements occurring in the direction of the toy, termed "*forward*" arm movements. Note that hand-toy distance in the toy condition was compared with the distance from the hand to the *virtual toy* location during the no toy condition. The virtual toy location was the average X, Y, and Z position of the toy during the 'toy' condition trials. **Planar hand position (mm):** The hand's position along the frontal axis (X), the sagittal axis (Y), and the vertical axis (Z) of the three-dimensional space at the end of forward arm movements (see Fig. 1A for coordinate frame). A decrease in frontal hand position indicates a midline movement of the hand. An increase in sagittal hand position indicates a forward movement of the hand. An increase in the vertical hand position indicates an upward movement of the hand.

Table 1
The total number of trials obtained for each infant at each visit

Infant initials	–10 weeks Early phase	–8 weeks	–6 weeks Mid phase	–4 weeks	–2 weeks Late phase	Week of reaching
AD						
No toy	4	7	6	6	6	7
Toy	4	6	6	7	6	7
AH						
No toy	6	4	7	6	6	6
Toy	4	5	7	6	6	6
BF						
No toy	6	7	6	6	6	6
Toy	8	7	6	7	7	6
DH						
No toy	6	No data	7	7	7	6
Toy	6	No data	8	7	8	6
IS						
No toy	N/A	6	6	7	7	5
Toy	N/A	7	7	7	7	6
JS						
No toy	6	8	6	6	5	6
Toy	7	8	7	7	5	6
JF						
No toy	7	7	6	7	No data	4
Toy	7	7	6	6	No data	5
KG						
No toy	6	8	6	7	7	6
Toy	6	6	6	7	7	8
LF						
No toy	N/A	6	4	7	7	6
Toy	N/A	6	4	8	7	7
NC						
No toy	6	6	7	7	6	7
Toy	6	6	7	7	6	7
PV						
No toy	5	7	7	6	7	6
Toy	5	7	6	6	7	7
SN						
No toy	8	6	No data	8	No data	7
Toy	8	7	No data	7	No data	7
SW						
No toy	8	6	7	5	7	7
Toy	8	6	7	7	8	7

“N/A” indicates the absence of data because infants reached with fewer than 10 sessions; “No data” indicates incomplete data that was not used due to excessive crying by the infant or absence as a result of illness.

5. Statistical analysis

The focus of this study was toy-oriented changes in arm movements across the weeks leading up to reach onset. Hence, all dependent variables were subjected to a two-way analysis of variance (ANOVA) with a repeated measures design wherein developmental time and experimental condition (no toy versus toy) were the two within-subject factors (Field, 2000). If the data for any dependent variable violated the sphericity assumption then the Greenhouse–Geisser

correction (if $\varepsilon^1 < 0.75$) or the Huynh–Feldt correction (if $\varepsilon > 0.75$) was performed and the alternative F -ratios and p -values are reported (Field, 2000). Post hoc analyses were conducted for the experimental condition through paired t -tests.

As expected, the number of visits up to onset of reaching varied across infants (Table 1). Thus, data were aligned to the week of reach onset (Thelen et al., 1993). Multiple dependent variables were calculated for each movement identified, values for all movements across all trials were averaged per condition; hence, each average value represents behavior across an entire experimental condition and not on a trial-by-trial basis. Also, as expected in longitudinal studies involving infants, there were a few missing data collections (6 out of a total of 78 spread across 5 infants). Hence, for the sake of conducting parametric statistics, such missing data points were filled by using the average value of a given dependent variable for that week because it represents the center of the data distribution of that variable for that week (Table 1). The mean and standard errors for each dependent variable are reported in figures. For all analyses, p -values < 0.05 were considered to be significantly different and p -values ≤ 0.1 were considered a statistical trend. Lastly, it is important that group findings are supported at the individual infant level, thus we also report the number of infants following each group result next to each p -value.

5.1. Weeks versus phases

Preliminary analysis suggested that adjacent weeks (–10 and –8 weeks, –6 and –4 weeks, –2 weeks and week of reach onset) showed similar toy-oriented changes (Fig. 1D). Paired t -tests confirmed that for all variables except hand–toy distance and frontal/sagittal/vertical hand positions, the toy-oriented difference between –10 and –8 weeks (Early phase), –6 and –4 weeks (Mid phase), –2 weeks and week of reach onset (Late phase) were not statistically different ($p > 0.2$). Hence, a 3 (phases: Early versus Mid versus Late) \times 2 (conditions: no toy versus toy) repeated measures ANOVA was used for the variables: movement number, length, speed, and number of velocity peaks. A 6 (weeks: 1–6) \times 2 (conditions: no toy versus toy) repeated measures ANOVA was used for the variables: hand–toy distance, frontal, sagittal, and vertical hand position. All statistical analyses were conducted using SPSS software (SPSS, Inc.). To be complete, figures show data both week-to-week and across phases.

6. Results

Movement number displayed an interesting mirrored U-shaped developmental pattern between the no toy and toy condition (Fig. 2A and B). Infants moved more often in the toy condition as compared to the no toy condition during the Mid phase (4–6 weeks before reaching), with no difference noted during the Early (8–10 weeks before reaching) and Late (0–2 weeks before reaching) phases. This pattern was reflected statistically as a significant main effect for condition, $F(1, 25) = 7.53, p = 0.01$, and a significant interaction between phase and condition, $F(2, 50) = 3.76, p = 0.03$. Post hoc analysis for toy-oriented change across phases confirmed that movement number significantly increased in the presence of a toy during the Mid phase (d.f. = 25, $p = 0.005$, 10 out of 13 infants followed this group finding).

The number of velocity peaks per movement, which reflected hand movement smoothness, also displayed a mirror U-shaped developmental pattern between the no toy and toy condition (Fig. 3A and B). Infants moved more smoothly in the toy condition as compared to the no toy condition during the Mid phase and with similar smoothness during the Early and Late phases. This pattern was reflected statistically as a significant main effect for condition, $F(1, 25) = 7.69, p = 0.01$, and a significant interaction between phase and condition, $F(2, 50) = 4.05, p = 0.024$. Post hoc analysis for toy-oriented change confirmed that the number of velocity peaks significantly decreased in the presence of a toy during the Mid phase (d.f. = 25, $p = 0.002$, 10 out of 13 infants followed this group finding).

Movement length during the toy and no toy conditions displayed a more complex developmental pattern than movement number or smoothness (Fig. 4A and B). Infants displayed a U-shaped pattern during the no toy condition with shorter hand movements during the Mid phase as compared to the Early and Late phases, whereas infants displayed a linear increase in movement length across phases during the toy condition. This resulted in a different relationship between the two experimental conditions during each phase. There was a statistical trend for an interaction between phase and condition, $F(1.69, 42.35) = 2.49, p = 0.10$. Post hoc analysis for toy-oriented change confirmed that movement

¹ ε is the Greenhouse–Geisser estimate and it varies between $1/(k-1)$ and 1. The closer the “ ε ” is to 1, the more homogenous the variance.

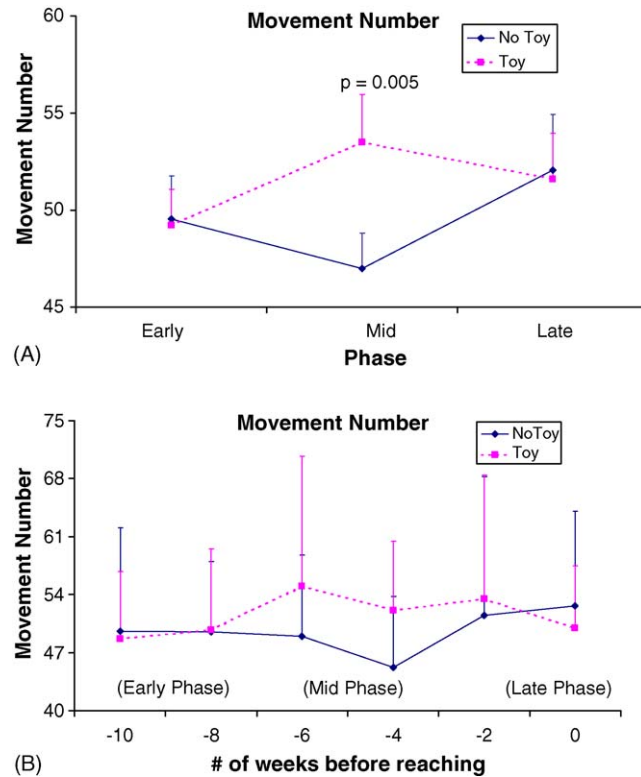


Fig. 2. The average movement number across movement phases (A) and across weeks (B) during the no toy and toy conditions. p -Values reflect comparisons between “no toy” and “toy”.

length significantly decreased in the presence of a toy during the Early phase (d.f. = 25, $p = 0.001$, 11 out of 13 infants followed this group finding).

Movement speed displayed a pattern of changes similar to that of movement length (Fig. 5A and B). Infants displayed a U-shaped pattern during the no toy condition with slower hand movements during the Mid phase as compared to the Early and Late phases, whereas infants displayed a linear increase in movement speed during the toy condition. This resulted in a different relationship between the two experimental conditions during each phase. Statistically, there was a significant main effect for condition, $F(1, 25) = 4.88$, $p = 0.037$, and a significant interaction between phase and condition, $F(2, 50) = 7.14$, $p = 0.002$. Post hoc analysis confirmed significant toy-oriented changes across two phases. During the Early phase, movement speed significantly decreased (d.f. = 25, $p = 0.01$, 11 of 13 infants) in the presence of a toy. In contrast, during the Mid phase, speed significantly increased in the presence of a toy (d.f. = 25, $p = 0.007$, 9 of 13 infants followed this group finding).

Minimum hand-toy distance reflected how close the infants' hands were to the toy at the closest point in each movement. Infants displayed a developmental pattern of hand-toy distance that differed from the previous variables (Fig. 6A). During the Mid phase, for the first time the majority of infants consistently decreased their hand-toy distance in the presence of a toy; however, this decrease was not statistically significant at the group level (9 out of 13 infants). During the Late phase, infants began to increasingly move their hands closer to the toy than to the virtual toy's position during no toy trials. Statistically, there was a significant main effect for week $F(5, 60) = 4.67$, $p = 0.001$, a significant main effect for condition $F(1, 12) = 17.99$, $p = 0.001$, and a significant interaction between week and condition $F(5, 60) = 10.9$, $p = 0.00$. Post hoc analyses confirmed a statistical trend for a decrease in hand-toy distance 2 weeks before reaching (d.f. = 12, $p = 0.08$, 9 out of 13 infants), and at the week of reaching (d.f. = 12, $p = 0.001$, all infants).

Planar hand position reflected the 3D planar positions of the infants' hands at the most forward point in each movement, and thus provided more specific information on how infants produced toy-oriented changes in hand-toy distance.

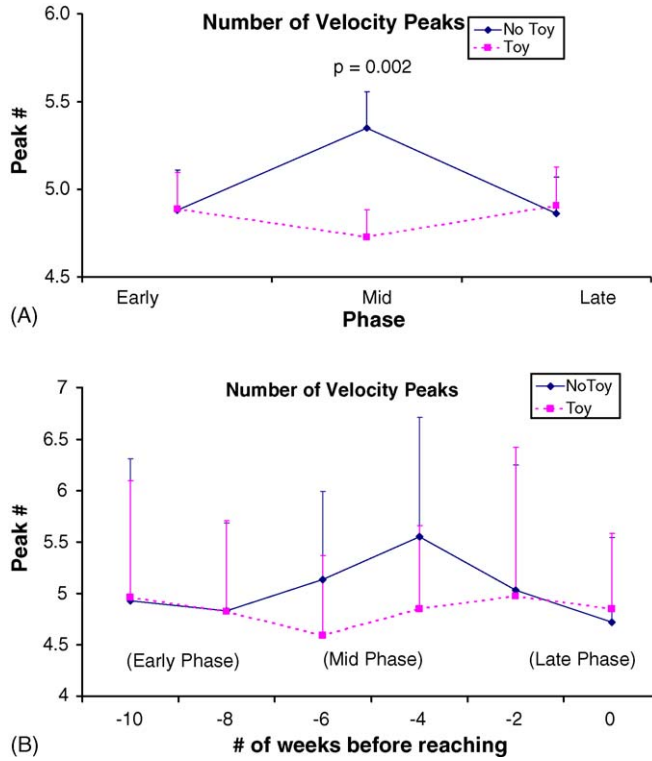


Fig. 3. The average number of velocity peaks across movement phases (A) and across weeks (B) during the no toy and toy conditions. *p*-Values reflect comparisons between “no toy” and “toy”.

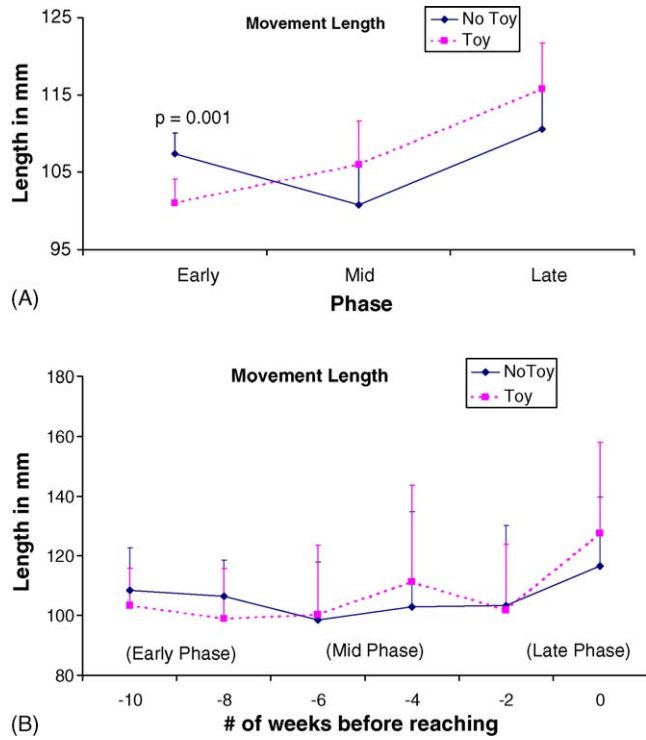


Fig. 4. Average movement length across movement phases (A) and across weeks (B) during the no toy and toy conditions. *p*-Values reflect comparisons between “no toy” and “toy”.

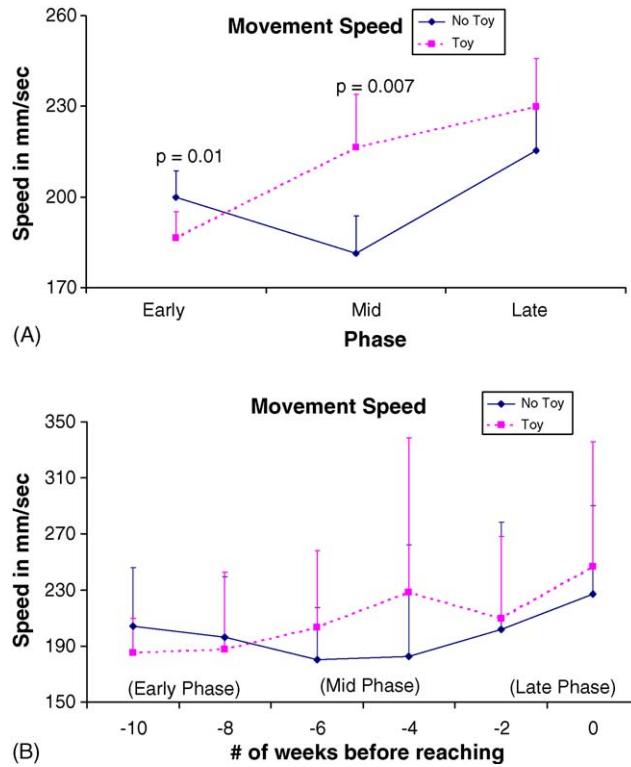


Fig. 5. Average movement speed across movement phases (A) and across weeks (B) during the no toy and toy conditions. *p*-Values reflect comparisons between “no toy” and “toy”.

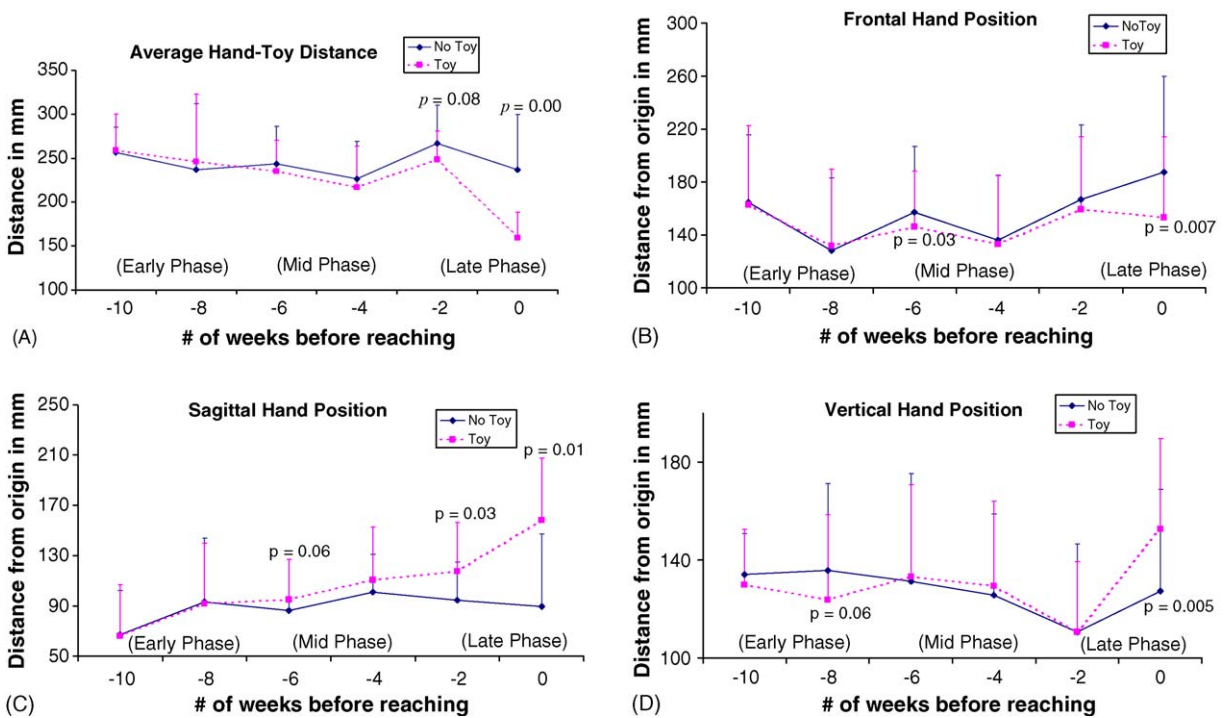


Fig. 6. Average data during no toy and toy conditions at each week for hand-toy distance (A) and hand position in the frontal (B), sagittal (C), and vertical (D) planes. *p*-Values reflect comparisons between “no toy” and “toy”.

6.1. Frontal plane (medial–lateral)

Overall, infants moved their hands more toward the midline in the presence of a toy in the last 6 weeks before reach onset, that is, across both Mid and Late phases (toy condition values less than no toy, Fig. 6B). There was a significant main effect for condition $F(1, 12)=7.67, p=0.017$ and a significant interaction between week and condition $F(5, 60)=3.43, p=0.009$. Post hoc analyses confirmed a significant decrease in the frontal hand position in the presence of a toy at 6 weeks before reaching (d.f. = 12, $p=0.014$, 9 out of 12 infants), and at the week of reach onset (d.f. = 12, $p=0.03$, 12 out of 13 infants).

6.2. Sagittal plane (anterior–posterior)

Overall, infants moved their hands increasingly more forward in the presence of a toy over the last 6 weeks before reaching, that is across both the Mid and the Late phases (toy condition values greater than no toy, Fig. 6C). There was a significant main effect for week $F(5, 60)=3.51, p=0.007$, a significant main effect for condition $F(1, 12)=34.65, p=0.00$, and a significant interaction between week and condition $F(5, 60)=12.53, p=0.00$. Post-hoc analyses confirmed a trend for an increase in sagittal plane position in the presence of a toy 6 weeks before reaching (d.f. = 12, $p=0.06$, 9 out of 12 infants) and a significant increase 2 weeks before reaching (d.f. = 12, $p=0.01$, 9 of 11 infants) and at the week of reach onset (d.f. = 12, $p=0.00$, 13 of 13 infants).

6.3. Vertical plane (superior–inferior)

In general, infants moved their hands progressively more downward in the presence of a toy 8 weeks before reaching (toy condition values less than no toy, Fig. 3D), then moved their arms more upwards in the presence of a toy by the week of reach onset (toy condition values greater than no toy, Fig. 6D). Statistically, there was a significant interaction between week and condition $F(5, 60)=3.67, p=0.006$. Post hoc analyses confirmed a statistical trend for a toy-oriented decrease in vertical plane motion 8 weeks before reaching (d.f. = 12, $p=0.06$, 9 of 13 infants) and a significant increase in vertical plane position at the week of reach onset (d.f. = 12, $p=0.001$, 11 of 13 infants).

In summary, when offered a toy, infants produced forward arm movements such that their hands moved downward during the Early phase; forward and midline during the Mid phase, and upward, forward, in midline during the Late phase. A qualitative comparison of the statistically significant toy-oriented changes in planar motion and in hand–toy distance suggested that forward, midline, and upward motion contributed significantly to the toy-oriented decrease in hand–toy distance during the Late phase.

7. Discussion

In general, our three hypotheses were upheld. First, infants displayed toy-oriented changes beginning many weeks before reaching. Second, the pattern of toy-oriented changes differed between the Early, Mid, and Late phases. Third, certain toy-oriented changes showed continuity between the week of reach onset and earlier weeks, whereas other toy-oriented changes were discontinuous, that is, specific to a particular developmental period or phase. Below, we briefly discuss our findings in relation to past work on the transition to purposeful reaching, and propose hypotheses for future work with infants at risk for dysfunctional reaching.

7.1. Toy-oriented changes in early arm movements

Early phase: When offered toys during the *Early phase* (8–10 weeks before reaching), infants decreased movement length and speed and moved their hands downward. This pattern of toy-oriented behavior was unique to the Early phase, i.e. this pattern was discontinuous with changes in the Mid phase (Table 2, Early phase column). These findings suggest that 8–10-week-old infants scaled down their movements when offered the toy. Moreover, these infants were very visually attentive to the toy (Atkinson, Hood, Wattam-Bell, & Braddick, 1992), which may have influenced the decrease in arm movements. A quieting of body movements with sustained attention to objects has been reported in young infants (Bacher & Robertson, 2001; Robertson et al., 2001; von Hofsten, 1984), and may reflect the ongoing development of the more general relationship between stimulus orienting and attention, and exploratory arm movements.

Table 2

Summary of toy-oriented changes: the table groups the toy-oriented changes during the Early, Mid, and Late phases

Toy-oriented Changes: Longitudinal			
Phases	Early Phase	Mid Phase	Late Phase
Wks before reach onset	-10 to -8	-6 to -4	-2 to 0
Movement Number			
Movement Length			
Movement Smoothness			
Movement Speed			
Hand-Toy Distance		CONTINUOUS	
Hand Position: Frontal		CONTINUOUS	
Hand Position: Sagittal		CONTINUOUS	
Hand Mean Position: Vertical			

White spaces indicate no change, black spaces indicate increase, and vertical bars indicate a decrease in the presence of a toy; 'Continuous' denotes variables that displayed a toy-oriented change during the Mid phase and then continued to show a change with greater magnitude in the Late phase.

Mid phase: When offered toys during the *Mid phase* (4–6 weeks before reaching), infants showed two types of toy-oriented changes: discontinuous and continuous (Table 2, Mid phase column). Discontinuous toy-oriented changes were those that were only seen in the Mid phase and suggested that this phase was one of increased activity and transition. Continuous toy-oriented changes were those that first emerged during the Mid phase and increased in magnitude during the Late phase. Continuous changes suggest a direct continuity between arm movements as early as 6 weeks before reach onset and the emergence of purposeful reaching (Table 2, Mid phase column).

Mid phase: discontinuous changes. First, infants increased the number of movements in the presence of a toy in agreement with other studies of 12–16-week-old infants (Galloway & Thelen, 2003; Thelen, 1981; von Hofsten, 1984). Second, infants showed a toy-oriented increase in the speed as was noted in our cross-sectional study (Bhat et al., 2005). Third, in addition to moving faster in the presence of a toy, infants in the Mid phase produced smoother movements (decreased number of velocity peaks per movement). This result would be confounded if movement length also showed a toy-oriented decrease during the Mid phase, however this was not the case. Several studies have noted an increase in reaching smoothness through the 2nd year of life if not longer (Konczak & Dichgans, 1997; Thelen, Corbetta, & Spencer, 1996; von Hofsten, 1991). Changes in *reaching* smoothness, however, may or may not reflect the same developmental processes as smoothness changes in the present study where infants were just beginning to control their non-reaching arm movements as well as much of the rest of their body. Below we briefly address this in more detail.

A reasonable assumption in older, reaching infants is that smoothness changes primarily reflect purposeful changes in arm control. Our results probably reflect a more general increase in the early control of movement and posture throughout the body, and the mechanical effects that unfolded thereafter. The majority of our infants decreased their hand–toy distance when offered toys, which may indicate purposeful attempts at contacting the toy (see discussion of Mid phase continuous changes below). Thus, the increased smoothness of these 'attempted' reaches may reflect an increase in purposeful control. It is important to note however that an increase in smoothness may have resulted at least in part from non-purposeful changes in muscle activity that increased stiffness (Lobo et al., 2004; Thelen et al., 1993) and/or changes in arm mechanics due to increased movement speed (Virji-Babul & Cooke, 1995). Previous studies have found a decrease in smoothness when movements became faster (Thelen et al., 1996; von Hofsten, 1991). However, these studies involved older infants whose arms may differ in stiffness as compared to the young infants in the present study. Clearly, the developmental processes underlying changes in movement quality during the prereaching period need further study.

Mid phase: continuous changes. First, the majority of infants decreased their hand–toy distance in the presence of a toy starting 6 weeks before reach onset as has been noted in other studies (Galloway & Thelen, 2003; Spencer & Thelen, 2000). Second, our results extend previous findings by noting that infants closed the hand–toy gap by moving their hands more in midline and forward positions with a toy present. In summary, the Mid phase was a significant time of change. Infants were transitioning through an active period in which they may have gained perceptual motor skill (discontinuous changes) from which they began to close the gap between their hands and the toy (continuous changes), and began to alter their arm movements in ways that would continue until the onset of reaching a month or more in the future.

Late phase. During the *Late phase* (within 2 weeks of reach onset), infants displayed both *continuous* changes continued from the Mid phase but with greater magnitude, and *discontinuous* changes seen only in the Late phase (Table 2, Late phase column). Continued from the Mid phase, infants decreased the hand–toy distance and eventually contacted the toy by moving their hands more in the midline and forward positions with a toy present. In addition, infants also moved their hands in the upward direction in the presence of a toy at the week of reach onset, which was rarely seen in previous weeks. Thelen et al. (1993) noted that, during the toy condition, infants either scaled up or scaled down their speed over the 2 weeks before reach onset. Although as a group, most of our infants increased their speed in the toy condition over this period, we did note individual variability. Our focus was on toy-oriented changes of which there were none in terms of movement speed. In summary, changes in the Late phase were positional. That is, within 2 weeks of their first reaches, infants were adapting their arm's position in the presence of toys but not our other measures. This may reflect that, by this period of development, the movement number, length, speed or smoothness of spontaneous arm movements (as reflected by our no toy condition) were each sufficient for infants to launch their first purposeful reaches. This provides additional empirical evidence that developmental changes in the quality and quantity of *spontaneous* arm movements are important foundations from which infants build purposeful reaching as has been proposed for many years (Thelen, 1979, 1981; Thelen et al., 1993; Turvey & Fitzpatrick, 1993; von Hofsten, 1993).

In addition to the toy-oriented changes in specific variables, there were three general findings that were interesting and require additional study. First, the use of three general developmental phases was useful in understanding how infants alter their hand kinematics in the presence of a toy during the prereaching period. More importantly, both group and individual data suggest that this phase analysis captured how infants were changing developmentally. From the Early to Late phases, infants scaled down their movements, then scaled up their movements to actively explore their arm's movements, then finally adapted the 3D position of their hands to begin contacting objects without changing the number, speed or smoothness characteristic of their spontaneous movements. Second, toy-oriented changes during the prereaching period were discontinuous and non-linear; as well as continuous and linear, the combination of which is a general hallmark of the emergence of complex behaviors (Michel & Moore, 1995). Although continuous changes are often more obviously connected to the emergence of later abilities, discontinuous or non-linear changes, such as the U-shaped patterns seen for movement number and smoothness, may well function as scaffolding upon which animals and humans build more complex behaviors such as reaching (Robinson & Smotherman, 1992). Last, an unexpected finding was that movement number and smoothness both exhibited similar mirror U-shaped patterns between the toy and no toy conditions; whereas length and speed exhibited patterns similar to each other but different from number and smoothness. Additional analysis is required to quantify the degree of similarity and the implications on the development of reaching. One intriguing possibility in terms of length and speed relationship is that these infants are beginning to display higher speeds for longer movements resulting in relatively constant movement times as is noted in adults reaching (Buneo, Soechting, & Flanders, 1994; Freund & Budingén, 1978; Hoffman & Strick, 1986; Pfann, Hoffman, Gottlieb, Strick, & Corcos, 1998). Indeed, such a proportional relationship appears in both the toy and no toy conditions with a linear increase in length and speed in the toy condition.

7.2. *Implications for at-risk infants*

The present study identified multiple toy-oriented changes in hand kinematics that can now be used as a normative database for future studies attempting to identify atypical movement patterns in populations at risk for reaching delays. To this end, we provide several general predictions for atypical early arm movements in one population, infants born significantly preterm.

In the Early phase, our infants visually engaged the toy and showed less arm movements. Preterm infants display prolonged gaze at objects, which persist longer into development than typically developing infants (Butcher, Kalverboer, Geuze, & Stremmelaar, 2002). Hence, preterm infants may decrease their movement number and speed in the presence of a toy for a prolonged period. In the Mid phase, our infants increased their movement number, speed, and smoothness, and decreased their hand–toy distance. Children born preterm may have impaired muscle tone and muscle performance (Monterosso, Kristjanson, Cole, & Evans, 2003; Samsom, DeGroot, Dick, Lafeber, & Fetters, 2002), impaired postural control (Wijnroks & van Veldhoven, 2003), and/or sensory-perceptual impairments (Therien, Worwa, Mattia, & dReregner, 2004; Vicari, Caravale, Carlesimo, Casadei, & Allemand, 2004; Wallace, Rose, McCarton, Kurtzberg, & Vaughan, 1995). These differences could contribute to differences in early arm kinematics such as jerky motions with an inability to move closer to the toy. In the Late phase, our infants displayed an exponential increase in the number of toy contacts over the last 2 weeks before reach onset. If preterm infants take longer to learn to control their arms (Fallang et al., 2003; Heriza, 1988a), then Mid phase changes may be prolonged resulting in very few successful toy contacts and delayed reaching.

7.3. Limitations and future studies

Although longitudinal designs provide important insight into developmental change, repeated exposures to a context and task can lead to habituation and learning effects outside of the typical developmental trajectory. Thus, future work should formally compare the complimentary views of cross-sectional and longitudinal designs. Our results are also constrained by the specificity of the experimental set up. For example, infants were offered toys in the midline as they sat in a custom made chair in a semi-reclined position with the upper trunk free to move. Future work across different body positions, object locations, and object properties are required to fully understand the development of purposeful reaching (Lobo et al., 2004; Out et al., 1998; van Hof, Van der Kamp, & Savelsbergh, 2002). This study focused on a subset of hand kinematics. It is important to continue to study early arm movements through additional hand variables as well as a comprehensive study of toy-oriented changes in joint kinematics. Non-biomechanical variables, such as those characterizing the interaction of infants, caregivers, and objects, are also critical to understanding the emergence of purposeful reaching. Lastly, each of these findings including the statistical trends were followed by a majority of infants. These findings, however, must be tested in future studies to determine the almost certain existence of subgroups reflecting individualized developmental trajectories.

Acknowledgements

We thank the families and infants for their enthusiastic participation; Mark Stanton, Slobodan Jaric, and John Scholz for their guidance throughout the project; John Scholz for assistance with the 3D kinematics; Jill Heathcock, Michele Lobo, and the many undergraduate research assistants for their assistance with data collection and analysis, and anonymous reviewers for their helpful comments. Funding for this project was from a grant from NIH NICHD #HD43830 to JCG, a University of Delaware Research Foundation award to JCG, and a University of Delaware Dissertation award to AB.

References

- Atkinson, J., Hood, B., Wattam-Bell, J., & Braddick, O. (1992). Changes in infants' ability to switch visual attention in the first three months of life. *Perception*, 21(5), 643–653.
- Bacher, L. F. (1998). A kinematic analysis of spontaneous arm movements in infants under different conditions of visual attention during the transition to reaching. *Unpublished developmental psychology*, Cornell University, Ithaca, NY.
- Bacher, L. F., & Robertson, S. S. (2001). Stability of coupled fluctuations in movement and visual attention in infants. *Developmental Psychobiology*, 39, 99–106.
- Berthier, N. E., Clifton, R. K., McCall, D. D., & Robin, D. J. (1999). Proximodistal structure of early reaching in human infants. *Experimental Brain Research*, 127, 259–269.
- Bhat, A. N., Heathcock, J. H., & Galloway, J. C. (2005). Toy-oriented changes in hand and joint kinematics during the emergence of purposeful reaching. *Infant Behavior and Development*, 28(4), 445–465.
- Buneo, C. A., Soechting, J. F., & Flanders, M. (1994). Muscle activation patterns for reaching: The representation of distance and time. *Journal of Neurophysiology*, 71, 1546–1558.

- Butcher, P. R., Kalverboer, A. F., Geuze, R. H., & Stremmelaar, E. F. (2002). A longitudinal study of the development of shifts of gaze to a peripheral stimulus in preterm infants with transient periventricular echogenicity. *Journal of Experimental Child Psychology*, 82(2), 116–140.
- Chen, Y., Fetters, L., Holt, K. G., & Saltzman, E. (2002). Making the mobile move: Constraining task and environment. *Infant Behavior and Development*, 25(2), 220–295.
- Cioni, G., Ferrari, F., Einspieler, C., Paolicelli, P. B., & Barbani, M. T. (1997). Comparison between observation of spontaneous movements and neurologic examination in preterm infants. *Journal of Pediatrics*, 130, 704–711.
- Corbetta, D., & Bojczyk, K. E. (2002). Infants return to two-handed reaching when they are learning to walk. *Journal of Motor Behavior*, 34(1), 83–95.
- Corbetta, D., Thelen, E., & Johnson, K. (2001). Motor constraints on the development of perception–action matching in infant reaching. *Infant Behavior and Development*, 23, 351–374.
- Diedrich, F. J., Highlands, T., Spahr, K., Thelen, E., & Smith, L. B. (2001). The role of target distinctiveness in infant perseverative reaching errors. *Journal of Experimental Child Psychology*, 78, 263–290.
- Eppler, M. A. (1995). Development of manipulatory skills and the deployment of attention. *Infant Behavior and Development*, 18, 391–405.
- Eyre, J. A., Miller, S., Clowry, G. J., Conway, E. A., & Watts, C. (2000). Functional corticospinal projections are established prenatally in the human fetus permitting involvement in the development of spinal motor centres. *Brain*, 123(1), 51–64.
- Eyre, J. A., Taylor, J. P., Villagra, F., Smith, M., & Miller, S. (2001). Evidence of activity-dependent withdrawal of corticospinal projections during human development. *Neurology*, 57(9), 1530–1531.
- Fallang, B., Saugstad, O. D., Grogaard, J., & Hadders-Algra, M. (2003). Kinematic quality of reaching movements in preterm infants. *Pediatric Research*, 53, 836–842.
- Field, A. (2000). Repeated measures design (GLM 3). In B. Glynis (Ed.), *Discovering statistics using SPSS for windows: Advanced techniques for the beginner* (pp. 323–374). London: Sage Publications.
- Fogel, A. (1992). Movement and communication in human infancy: The social dynamics of development. *Human Movement Sciences*, 11, 387–423.
- Fogel, A., Dedo, J. Y., & McEwen, I. (1992). Effect of postural position and reaching on gaze during mother infant face-to-face interaction. *Infant Behavior and Development*, 15(2), 231–244.
- Freund, H. J., & Budinggen, H. J. (1978). The relationship between speed and amplitude of the fastest voluntary contractions of human arm muscles. *Experimental Brain Research*, 31, 1–12.
- Galloway, J. C., & Thelen, E. (2003). Feet first: Object exploration in human infants. *Infant Behavior and Development*, 27(1), 107–112.
- Gert van Dijk, J., Pondaag, W., & Malessy, M. J. A. (2001). Obstetric lesions of the brachial plexus. *Muscle and Nerve*, 11, 1451–1461.
- Goldfield, E. (1990). Transition from rocking to crawling: Postural constraints on infant movement. *Developmental Psychology*, 25(6), 913–919.
- Hadders-Algra, M., & Precht, H. F. R. (1992). Developmental course of general movements in early infancy. I. Descriptive analysis of change in form. *Early Human Development*, 28(3), 201–213.
- Heriza, C. B. (1988a). Comparison of leg movements in preterm infants at term with healthy full-term infants. *Physical Therapy*, 68, 1687–1693.
- Heriza, C. B. (1988b). Organization of leg movements in preterm infants. *Physical Therapy*, 68, 1340–1346.
- Hoffman, D. S., & Strick, P. L. (1986). Step-tracking movements of the wrist in humans. I. Kinematic analysis. *Journal of Neuroscience*, 6, 3309–3318.
- Kawai, M., Savelsbergh, G. J., & Wimmers, R. H. (1999). Newborns spontaneous arm movements are influenced by the environment. *Early Human Development*, 54(1), 15–27.
- Konczak, J., Borutta, M., Topka, H., & Dichgans, J. (1995). The development of goal-directed reaching in infants: Hand trajectory formation and joint torque control. *Experimental Brain Research*, 106, 156–168.
- Konczak, J., & Dichgans, J. (1997). The development toward stereotypic arm kinematics during reaching in the first 3 years of life. *Experimental Brain Research*, 117, 346–354.
- Lew, A. R., & Butterworth, G. (1997). The development of hand–mouth coordination in 2- to 5-month-old infants: Similarities with reaching and grasping. *Infant Behavior and Development*, 20(1), 59–69.
- Lobo, M. A., Galloway, J. C., & Savelsbergh, G. (2004). General and task-related experiences affect early object interaction. *Child Development*, 75(4), 1268–1281.
- Martin, J. H., Choy, M., Pullman, S., & Meng, Z. (2004). Corticospinal system development depends on motor experience. *Journal of Neuroscience*, 24(9), 2122–2132.
- Martin, J. H., Engber, D., & Meng, Z. (2005). Effect of forelimb use on postnatal development of the forelimb motor representation in primary motor cortex of the cat. *Journal of Neurophysiology*, 93, 2822–2831.
- Michel, G. F., & Moore, C. L. (1995). Behavioral embryology. In G. F. Michel & C. L. Moore (Eds.), *Developmental psychobiology* (pp. 289–332). Boston: MIT Press.
- Monterosso, L., Kristjanson, L., Cole, J., & Evans, S. (2003). Effect of postural supports on neuromotor function in very preterm infants to term equivalent age. *Journal of Paediatrics and Child Health*, 39(3), 197–205.
- Out, L., Savelsbergh, G. J. P., van Soest, A. J., & Hopkins, B. (1997). Influence of mechanical factors on movement units in infant reaching. *Human Movement Science*, 16(6), 733–749.
- Out, L., van Soest, A. J., Savelsbergh, G. J. P., & Hopkins, B. (1998). The effect of posture on early reaching movements. *Journal of Motor Behavior*, 30(3), 260–272.
- Pfann, K. D., Hoffman, D. S., Gottlieb, G. L., Strick, P. L., & Corcos, D. M. (1998). Common principles underlying the control of rapid, single degree-of-freedom movements at different joints. *Experimental Brain Research*, 118, 35–51.
- Piek, J. P. (1998). The influence of preterm birth on motor development. In J. P. Piek (Ed.), *Motor behavior and human skill: A multidisciplinary approach*. Champaign, IL: Human Kinetics Publishers, Inc.
- Piek, J. P., & Carman, R. (1994). Developmental profiles of spontaneous movements in infants. *Early Human Development*, 39, 109–126.

- Precht, H. F. R., & Hopkins, B. (1986). Developmental transformations of spontaneous movement in early infancy. *Early Human Development*, *14*, 233–238.
- Robertson, S. S. (1993). Oscillation and complexity in early infant behavior. *Child Development*, *64*, 1022–1035.
- Robertson, S., Bacher, L. F., & Huntington, N. L. (2001). The integration of body movement and attention in young infants. *Psychological Science*, *12*(6), 523–526.
- Robinson, S. R., & Smotherman, W. P. (1992). Fundamental motor patterns of the mammalian fetus. *Journal of Neurobiology*, *23*, 1574–1600.
- Rochat, P. (1989). Object manipulation and exploration in 2- to 5-month old infants. *Developmental Psychology*, *25*, 871–884.
- Samsom, J. F., DeGroot, L., Dick, B., Lafeber, H., & Fetters, W. (2002). *Muscle power development during the first year of life predicts neuromotor behaviour at 7 years in preterm born high-risk infants*, *68*(2), 103–118.
- Spencer, J. P., & Thelen, E. (2000). Spatially specific changes in infant's muscle coactivity as they learn to reach. *Infancy*, *1*(3), 275–302.
- Spencer, J., Vereijken, B., Diedrich, F., & Thelen, E. (2000). Posture and emergence of manual skills. *Developmental Science*, *3*(4), 216–233.
- Thelen, E. (1979). Rhythmic stereotypies in normal human infants. *Animal Behavior*, *27*, 699–715.
- Thelen, E. (1981). Kicking, rocking and waving: Contextual analysis of rhythmical stereotypies in normal human infants. *Animal Behavior*, *29*, 3–11.
- Thelen, E. (1985). Developmental origins of motor coordination: Leg movements in human infants. *Developmental Psychobiology*, *18*, 1–22.
- Thelen, E. (1994). Three-month-old infants can learn task-specific patterns of interlimb coordination. *Psychological Science*, *5*(5), 280–285.
- Thelen, E., Corbetta, D., Kamm, K., Spencer, J., Schneider, K., & Zernicke, R. F. (1993). The transition to reaching: Mapping intention and intrinsic dynamics. *Child Development*, *64*, 1058–1098.
- Thelen, E., Corbetta, D., & Spencer, J. (1996). Development of reaching during the first year: Role of movement speed. *Journal of Experimental Psychology: Human Perception and Performance*, *22*(5), 1059–1076.
- Thelen, E., & Fisher, D. M. (1983). The organization of spontaneous leg movements in newborn infants. *Journal of Motor Behavior*, *15*(4), 353–377.
- Thelen, E., Schöner, G., Scheier, C., & Smith, L. B. (2001). The dynamics of embodiment: A field theory of infant perseverative reaching. *Behavioral and Brain Sciences*, *24*, 1–34.
- Therien, J. M., Worwa, C. T., Mattia, F. R., & dReregner, R. A. (2004). Altered pathways for auditory discrimination and recognition memory in preterm infants. *Developmental Medicine and Child Neurology*, *46*(12), 816–824.
- Tronik, E. Z., Fetters, L., Olson, K. L., & Chen, Y. (2004). Similar and functionally typical kinematic reaching parameters in 7- and 15-month old in utero cocaine exposed and unexposed infants. *Developmental Psychobiology*, *44*, 168–175.
- Turvey, M. T., & Fitzpatrick, P. (1993). Commentary: Development of perception–action systems and general principles of pattern formation. *Child Development*, *64*, 1175–1190.
- van Hof, P., Van der Kamp, J., & Savelsbergh, G. J. P. (2002). The relation of unimanual and bimanual reaching to crossing the midline. *Child Development*, *73*(5), 1353–1362.
- Vicari, S., Caravale, B., Carlesimo, G. A., Casadei, A. M., & Allemand, F. (2004). Spatial working memory deficits in children at ages 3–4 who were low birth weight, preterm infants. *Neuropsychology*, *18*(4), 673–678.
- Virji-Babul, N., & Cooke, J. D. (1995). Influence of joint interactional effects on the coordination of planar two-joint arm movements. *Experimental Brain Research*, *103*(3), 451–459.
- von Hofsten, C. (1982). Eye–hand coordination in the newborn. *Developmental Psychology*, *18*(3), 450–461.
- von Hofsten, C. (1984). Developmental changes in the organization of pre-reaching movements. *Developmental Psychology*, *20*(3), 378–388.
- von Hofsten, C. (1991). Structure of early reaching movements: A longitudinal study. *Journal of Motor Behavior*, *23*(4), 280–292.
- von Hofsten, C. (1993). Prospective control: A basic aspect of action development. *Human Development*, *36*, 253–270.
- von Hofsten, C., & Ronnqvist, L. (1993). The structuring of neonatal arm movements. *Child Development*, *64*, 1046–1057.
- Wallace, I. F., Rose, S. A., McCarton, C. M., Kurtzberg, D., & Vaughan, H. G. J. (1995). Relations between infant neurobehavioral performance and cognitive outcome in very low birth weight preterm infants. *Journal of Developmental and Behavioral Pediatrics*, *16*(5), 309–317.
- Wijnroks, L., & van Veldhoven, N. (2003). Individual differences in postural control and cognitive development in preterm infants. *Infant Behavior and Development*, *26*(1), 14–26.
- Zelazo, P. R., Zelazo, N. A., & Kolb, S. E. (1972). Newborn walking. *Science*, *177*, 1058–1059.