ABSTRACT: Adult hand preference emerges from complex developmental changes in arm and hand use during childhood. Recent reports have highlighted the importance of understanding arm and hand use during the first year of life including the period before reach onset. This longitudinal study tested the hypothesis that significant right–left differences exist in pre-reaching arm movements. We examined right and left hand kinematics from 13 healthy infants during trials with and without a toy present from 8 weeks of age through the week of reach onset. Significant right–left differences were found, however there was no clear pattern within a condition or across conditions. Without a toy present, the right hand moved faster, yet ended further from midline, and displayed more movements during the Late phase compared to other phases. With a toy present, the right hand moved longer lengths, yet ended movements further away from the toy. When left and right hand kinematics were combined, previous findings of right hand kinematics alone were supported. Although infants begin adapting their pre-reaching kinematics many weeks before reach onset, we did not find evidence of a systematic right–left difference before reach onset in movements with or without a toy present. Our results, coupled with other reports, suggest hand asymmetries begin to emerge over the year following reach onset amid developmental changes both within the infant, and the physical and social environment. © 2008 Wiley Periodicals, Inc. Dev Psychobiol 50: 390–398, 2008.

Keywords: infant; reaching; motor; handedness; laterality

INTRODUCTION

Hand dominance is the predominant use of one hand versus the other in daily tasks. Consistent hand dominance allows humans efficient use of tools, written communica-

tion, and self care activities (Corey, Hurley, & Foundas, 2001; Phillips, Gallucici, & Bradshaw, 1999). In 70–90% of the population the right hand is preferred to complete functional tasks such as writing, throwing and using a spoon during a standardized test, or a combination of tasks and tests (Bryden & Steenhuis, 1991; Oldfield, 1971; Porac & Coren, 1981). In adults, dominant and non-dominant arms display differences across a range of variables during experimental tasks. For example, the dominant arm had faster reaction time (Fitts, 1992) and movement time (Keele & Posner, 1968), greater torque coordination between elbow and shoulder (Bagesterio & Sainberg, 2002) and stronger force production in grip testing (Petersen, Petrick, Connor, & Conklin, 1989). The dominant and non-dominant arms had different hand path
curvatures and joint coordination during point-to-point reaches to near and far targets (Sainburg & Kalakanis, 2000). Differences in crossed limb learning have also been reported (Criscimanga-Hemming, Dunchin, Gazzaniga, & Shadnur, 2003; Wang & Sainburg, 2006). Interestingly, loss of arm and hand function as a result of stroke was best regained in right-handers sustaining a left sided lesion (McCombe-Waller & Whittall, 2006) with distinctive cortical re-organization patterns between dominant and non-dominant hand (Zemke, Heagerty, Lee, & Cramer, 2003). The lack of clear hand dominance is also a feature of certain psychiatric disorders in humans and animal models (Branson & Rogers, 2006; Boscaino & Hoffman, 2007; Sommer, Aleman, Ramsey, Bouma, & Kahn, 2001). In summation, handedness is a common feature of human behavior and is associated with stable, functional nervous system organization.

Hand dominance becomes increasingly stable over the first 3–4 years of life (Corbetta & Thelen, 1996, 1999; McManus, 2002). Corbetta and Thelen (1999), in the most comprehensive study to date on early reaching, found that infants fluctuated in hand speed between arms throughout the first year of life. Moreover, the asymmetry of infants’ non-reaching movements were related to their reaching asymmetry. More recently reaching differences were found in select variables in infants as young as 6 months of age (Ronnqvist & Domellof, 2006). Infants 7–13 months of age displayed progressively fewer movement units, straighter hand path, decreases in peak velocity for the right hand, and overall an adult like ratio of right hand to non-reaching movements were related to their reaching asymmetry. More recently reaching differences were found in select variables in infants as young as 6 months of age (Ronnqvist & Domellof, 2006). Infants 7–13 months of age displayed progressively fewer movement units, straighter hand path, decreases in peak velocity for the right hand, and overall an adult like ratio of right hand preference for reaching towards toys (Corbetta, 2003; Michel, Sheu, & Brumley, 2002; Michel, Tyler, Ferre, & Sheu, 2006; Ronnqvist & Domellof, 2006) By 12 months of age, infants reliably chose a stabilizing hand and a manipulating hand during bilateral play with toys, however they fluctuated in terms of which is the stabilizing hand (Fagard & Peze, 1997). By 3–4 years of age, toddlers consistently displayed a skilled, dominant hand in more complex manual activities (Corbetta & Thelen, 1996, 1999; McManus, 2002).

This project addresses three gaps in our understanding of the development of hand dominance. First, studies of hand dominance typically have focused upon reaching and grasping after reach onset. Corbetta and Thelen (1999) did not note significant asymmetry in their microdevelopmental analysis of speed differences in four infants in the weeks up to reach onset, however Ronnqvist and Domellof (2006) found fewer movement units with the right hand in reaching infants as young as 6 months of age. Second, studies of hand dominance during reaching have focused on limb asymmetries during tasks with a toy present. Work from our lab and others have suggested important developmental connections between the kinematics and coordination of spontaneous arm movements and movements with a toy present over the pre-reaching and reaching periods of early infancy (Bhat & Galloway, 2006, 2007; Corbetta & Thelen, 1999; Kawai, Savelsbergh, & Wimmers, 1999; Thelen et al., 1993; Van der Fits, Klip, van Eykeren, & Hadders-Algra, 1999). Third, there are few longitudinal studies of limb asymmetry differences in early infancy. Our longitudinal study sought to address these gaps by testing for hand asymmetries across multiple variables during the pre-reaching period in movements with and without a toy present.

Thus, the specific purpose of this project was to test the hypothesis that significant left–right arm differences exist in hand kinematics longitudinally over the pre-reaching period in movements with and without a toy present. If left–right differences are present in pre-reaching movements, then arm asymmetries are not simply linked with the onset of purposeful reaching. Rather, such differences would reflect constraints inherent in pre-reaching movements. Such organismal constraints have been identified in pre-reaching arm movements, and proposed to be important to the development of reaching (Bhat & Galloway, 2007; Bhat, Lee, & Galloway, 2007). If left–right differences are not present in pre-reaching movements, then these differences would appear to emerge rapidly between the onset of reaching at 3–5 months of age and 6–7 months of age, when the first left–right arm differences are noted (Michel, Sheu, & Brumley, 2002; Michel, Tyler, Ferre, & Sheu, 2006; Ronnqvist & Domellof, 2006). Moreover, such left–right differences found in object oriented movements could then be attributed to further development of neural control as opposed to organismic constraints such as genetics. Such rapid emergence has been noted between reaching without grasping to reaching with grasping (Wimmers, Savelsbergh, Beek, & Hopkins, 1998) and with early postural control (Hedberg, Forssberg, & Hadders-Algra, 2004).

METHODS

Participants

Thirteen healthy, full term infants were recruited from the Newark, Delaware community through public birth announcements. Infants (eight females and five males) entered the study at 8 weeks of age and were observed every other week up to the week of reach onset (average week of reach onset was 19.5 weeks of age ±2.4 weeks). Week of reach onset was defined as the first week that total toy contacts were three times greater than any previous week. A single experimenter coded the toy contacts for all infants. Paired samples correlations on 572 contacts across 12 infants found very high intra-rater reliability (r = .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...
infant illness or crying for >2 min. Infants were admitted in the study following informed parental consent as approved by the University of Delaware Human Subjects Review Board.

**Procedure**

Caregivers placed infants in a seated position in a custom chair, reclined at 30° from the vertical (Fig. 1). The chair allowed for full, free range of motion of both the arms and the legs. Infants participated in blocked condition trials, with 6, 30-s trials of two conditions: toy and no toy. For the “no toy” condition, an experimenter was seated in front of the infant and spoke to the infant. We use the no toy condition to reflect nonobject oriented movements similar to the spontaneous movements that would occur throughout the day in prereaching infants. During the “toy” condition, a toy was presented at the child’s midline at the infant’s shoulder height, and at the midpoint between both shoulders. We placed the toy at 80% of arm length. Thus, the infant’s physical growth did not alter the reaching distance. The order of these was alternated between visits. An average of 6.4 ± .92 trials, 30 s long were recorded for each condition (see Bhat & Galloway, 2006, Table 1). Babies were awake, alert, and not crying during data collections.

**Data Capture and Analysis**

A six camera (120 Hz) Vicon Motion Capture system (Vicon Motion Systems, Inc., Lake Forest, CA) in a semicircular position surrounded the infant chair to obtain data from both arms, with a calibrated volume of 160 cm × 160 cm × 200 cm. Data was collected using six non-linear, reflective marker arrays, each of which had three 8 mm diameter markers. Markers were placed as follows: 1 on the dorsum of the hand, 1 at the forearm, and 1 at the humeral head of each hand. A marker was also placed on the toy. For each trial, the 3D position for each marker was calculated and filtered at 4 Hz with a 4th order Butterworth filter. We calculated the 3D linear position of the hand, then the 3D resultant speed of hand using a three-point differentiation technique with custom Matlab programming (Mathworks, Inc., Natick, MA). An average of 6 min of motion data (3.5 ± .062 min per condition) were recorded per infant per session. A loss of no more than 10 consecutive frames of marker position data (1/12th of a second) was interpolated using cubic spline interpolation. Following the interpolation, greater than 95% of the recorded data per experimental condition per infant were used for further analysis, which matches the amount of data used by similar studies (Thelen et al., 1993; von Hofsten & Rönnqvist, 1993).

**Data Analysis**

**Movement Identification.** All dependent variables were analyzed per movement for both the right and left side. A “movement” was operationally defined as 3D hand displacement ≥30 mm in length. Our goal was to capture all types of movements, small as well as large; hence, we used a threshold of 30 mm. (see previously published methodology from Bhat & Galloway, 2006). The end of a preceding movement and the start of the next movement were defined by a movement reversal of ≥15 mm (see Bhat & Galloway, 2006, their Fig. 1B and C). A custom Matlab program identified the movements and an experimenter visually selected each movement by observing the Matlab produced 3D hand position profile. Matlab then confirmed the selected movements based upon the set criteria, to ensure reliability of selected movements. For each movement, multiple dependent variables were calculated, as described below.

**Table 1.** Shows the Total Number of Movements, Total Toy Contacts and Success Ratio From the Week of Reach Onset for Each Infant and for the Group

<table>
<thead>
<tr>
<th>Infant</th>
<th>Movement Number</th>
<th>Contacts</th>
<th>Contact Success Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Right Left</td>
<td>Right Left</td>
<td>Right Left</td>
</tr>
<tr>
<td>AD</td>
<td>81 96</td>
<td>13 20</td>
<td>16.0 20.8</td>
</tr>
<tr>
<td>AH</td>
<td>133 101</td>
<td>28 23</td>
<td>21.1 22.8</td>
</tr>
<tr>
<td>BF</td>
<td>86 86</td>
<td>17 28</td>
<td>19.8 32.6</td>
</tr>
<tr>
<td>DH</td>
<td>118 70</td>
<td>10 1</td>
<td>8.5 1.4</td>
</tr>
<tr>
<td>IS</td>
<td>99 125</td>
<td>15 8</td>
<td>15.2 6.4</td>
</tr>
<tr>
<td>JS</td>
<td>153 109</td>
<td>29 12</td>
<td>19.0 11.0</td>
</tr>
<tr>
<td>JF</td>
<td>83 107</td>
<td>2 6</td>
<td>2.4 5.6</td>
</tr>
<tr>
<td>KG</td>
<td>176 132</td>
<td>32 15</td>
<td>18.2 11.4</td>
</tr>
<tr>
<td>LF</td>
<td>152 148</td>
<td>39 32</td>
<td>25.7 21.6</td>
</tr>
<tr>
<td>NC</td>
<td>167 118</td>
<td>53 21</td>
<td>31.7 17.8</td>
</tr>
<tr>
<td>PV</td>
<td>129 126</td>
<td>6 28</td>
<td>4.7 22.2</td>
</tr>
<tr>
<td>SN</td>
<td>187 137</td>
<td>30 6</td>
<td>16.0 4.4</td>
</tr>
<tr>
<td>SW</td>
<td>154 136</td>
<td>24 11</td>
<td>15.6 8.1</td>
</tr>
<tr>
<td>Average</td>
<td>132.2 114.7</td>
<td>22.9 16.2</td>
<td>16.4 14.3</td>
</tr>
<tr>
<td>STD</td>
<td>36.4 22.5</td>
<td>14.3 9.9</td>
<td>8.0 9.3</td>
</tr>
</tbody>
</table>
**Dependent Variables**

**Movement Length**: The distance, in millimeters, of each movement of each hand between the hand location at start frame and the hand location at the end frame. **Speed of hand movement**: The average 3D speed of each hand motion, in millimeters per second, over each full movement. **Number of velocity peaks (movement smoothness)**: The average number of velocity peaks of each hand within each full movement. The lower the average number of velocity peaks, the more smooth the movement (Ronnqvist & Domellof, 2006; Von Hofsten, 1991). **Movement frequency (movement per minute)**: The total number of hand movements normalized by the total duration of all trials per condition. **Hand toy distance**, reported for the “towards” movements in the toy condition (and towards a virtual mid-point in the no toy condition) represents the minimal distance between the hand to toy at the end of a movement. **Contact number**: Contact number represents the total number of contacts of the infant hand to the toy during the toy condition. Contacts were coded by analysis of video data. **Total movement number**: The total number of movements produced in the toy condition only. **Contact success ratio**: Total number of contacts divided by total number of movements multiplied by 100.

**Statistical Analysis**

Movement length, speed, smoothness, frequency, and hand toy distance were each entered into a separate three factor analysis of variance (ANOVA) with repeated measures design with a significant level of $p < .05$. Data was collated by developmental phases of “Early” (8–10 weeks before reaching), “Mid” (4–6 weeks before reaching), and “Late” (within 2 weeks of reaching) (see Bhat & Galloway, 2006). Data points reflect each infant’s average data across trials of a condition within each phase. Hand (right and left), condition (toy and no toy) and phase (Early, Mid, Late) were the three within subject factors. If the data for any dependent variable violated the sphericity assumption, then the Greenhouse-Geisser correction (if epsilon < .75) or the Huynh-Feldt correction (if epsilon > .75) was performed and the alternative F-ratios and $p$ values are reported. When interaction effects were identified, post hoc analyses were conducted to determine significance between factors. As a secondary analysis, right and left data points were collapsed as part of the omnibus analysis under the “condition” factor. This allowed a comparison between results with right and left data combined, and the right hand only data previously reported (Bhat & Galloway, 2006).

**RESULTS**

**Movement Length**

There was no significant main effect of condition, side, or time in the variable of movement length. A significant interaction effect was found in both condition by time ($F(1, 24) = 3.849, p < .05$) and side by time ($F(2, 24) = 3.586, p < .05$). Post hoc analysis of the condition by time interaction found, in the no toy condition, a significant increase in length of movements from the mid and late phase of development ($F(2, 11) = 5.086, p < .05$) (Fig. 2A). In the Toy condition, there was also a significant increase in length of movements between Early and Late phases ($F(2, 11) = 10.195, p < .01$; Fig. 2A). Post hoc analysis of the side by time interaction revealed a significant increase in length of movement over time ($F(2, 11) = 16.269, p < .01$) only for the left hand (Fig. 2B).

**Speed of Hand Movement**

There was no significant main effect of side in the variable of speed. There was a significant main effect of time ($F(1, 12) = 3.494, p < .05$), finding that, when left and right data are pooled across time within each condition, there is an increase in speed between Early and Late phases in both toy and no toy conditions. (Fig. 3A) There was a significant interaction effect in condition by side ($F(1, 12) = 7.959, p < .05$). Post hoc analysis of the interaction in condition by side identified that in the no toy condition

![FIGURE 2](image-url) (A) Shows movement length changes over time in both conditions, collapsing right and left side data in each condition; (B) shows right and left hand movement length, collapsing both conditions in each side.
the right hand consistently moved faster than the left hand ($F(1, 12) = 3.417, p = .089$; Fig. 3B).

**Number of Velocity Peaks (Movement Smoothness)**

There were no significant main effects of condition, side, or time found in the number of velocity peaks. There were no interaction effects among side, condition, or time in smoothness (no figure).

**Movement Frequency**

There were no significant main effects of condition, side, or time found in the movements per minute. There was an interaction effect in side by condition by time, only in the no toy condition with greater frequency of right sided movements in the Late phase ($F(1, 12) = 6.16, p < .05$; Fig. 4).

**Hand Toy Distance**

There were significant main effects for side ($F(1, 12) = 182.13, p < .01$), condition ($F(1, 12) = 150.97, p < .01$), and time ($F(1, 12) = 6.37, p < .01$). However, there were also interaction effects in condition by side ($F(1, 12) = 146.1, p < .01$) and in condition by time ($F(2, 24) = 18.87, p < .01$). Post hoc analysis of the interaction between conditions by side found two effects. The right hand was further away from the toy at the end of movements than the left in both the no toy condition ($F(1, 12) = 257.56, p < .01$; Fig. 5A) and the toy condition ($F(1, 12) = 6.46, p < .01$; Fig. 5B). Post hoc analysis of the interaction between condition by time found a significant effect only in the toy condition, with decreased distance across developmental phases regardless of hand ($F(2, 11) = 18.36, p < .01$; Fig. 5C).

**Contact Success Ratio**

Although we did not identify consistent right–left differences during pre-reaching movements, infants may have shown a right–left difference in their initial toy contacts during the week of reach onset. This was, however, not the case. There was only a 2% difference between the contact success ratio, which is the percent of hand movements contacting the toy, between the right hand (16%) and left hand (14%). This was not a significant difference between limbs on dependent t test [$t(12) = 150.97, p > .05$]. See Table 1 for individual and group data on the total movement number, toy contacts and success ratio.

**DISCUSSION**

This longitudinal study tested the hypothesis that significant right–left differences exist in pre-reaching arm movements. Although we identified differences involving different variables, there was no consistent pattern within a condition or across conditions. For example, in movements without a toy present, the right
hand moved faster, yet ended further from midline across all developmental phases compared to the left hand, and displayed more movements during the Late phase compared to other phases. These results do not provide strong evidence of a systematic right–left difference in pre-reaching arm movements with or without a toy present.

The lack of consistent asymmetry, however, did provide the opportunity to combine left and right hand data to test our previous findings on pre-reaching movements of the right hand (Bhat & Galloway, 2006). Our results support previous work that suggested pre-reaching movements with and without a toy differ in movement length, speed, and hand-toy distance. Specifically, for both arms, Early phase movements were shorter and slower, while Mid phase changes included increased movement number, increased speed, and decreased hand toy distance when a toy is present. These results support our previous proposal that infants begin altering their ongoing spontaneous arm movements when offered toys many weeks, if not months, before their first reaches.

Given our results, we propose that hand asymmetry leading to hand dominance for reaching begins to emerge during a developmental window of time after reach onset. Our results, coupled with those of Ronnqvist and Domellof (2006) and Michel et al. (2002, 2006), suggest hand asymmetries emerge between reach onset and the end of the first year, which is a similar period to other lateral preferences such as at the foot and eye (Coren, Porac, & Duncan, 1981; Handa et al., 2004). It is important to note that this window is not when infants display stable hand dominance, but rather when the first tractable experimental evidence of hand asymmetry is displayed. As highlighted by Corbetta and Thelen (1999), hand preference is characteristically dynamic, displays developmentally important fluctuations within and across contexts throughout the first year of reaching, and is far from stable until much later in childhood. Indeed, we propose this developmental window is an important focal period from which to build future theoretical and empirical work towards a comprehensive understanding of the process of hand dominance development.

Current theories of the origin of hand dominance have focused on the interaction of intrinsic and extrinsic factors (Hopkins & Cantero, 2003; Tang & Verstynen, 2002). The purpose of the current study was not to provide a test of any specific theory. Knowledge that strong hand asymmetries emerge after reach onset, however supports several issues proposed to be important in understanding the developmental origins of handedness as outlined below (Michel, Tyler, Ferre, & Sheu, 2006; Michel, Sheu, & Brumley, 2002).

First, functional hand asymmetry for reaching emerges, at least in part, out of infants’ exploration of their new skills of reaching and grasping. Intrinsic processes such as those proposed by the ‘right-shift gene’ theory (Annett, 2004), and dextral-chance alleles (McManus, 2002) reflect the increasing interest in the molecular basis of handedness. Although these and certainly many other intrinsic factors acting via neurobiological processes influence hand dominance, our results suggest that these processes do not strongly influence early asymmetry until after infants gain some level of reaching and grasping experience. This has theoretical importance as it argues against any one factor resulting in a predestined reaching preference (Corbetta & Thelen, 1999; Michel & Harkins, 1986; Michel, Tyler, Ferre, & Sheu, 2006; Michel, Sheu, & Brumley, 2002). Rather, our results argue for a multifactor process heavily reliant on infants gaining information via object exploration. Indeed, it is clear that through visual and haptic exploration, infants become increasingly sensitive to task oriented constraints such as the range of object qualities during the 2nd half of the first year (Braswell et al., 2007; Corbetta, Williams, & Snapp-Childs, 2006; Gibson, 1988; Gibson & Walker, 1984; Lederman & Klatzky, 1987).

To be clear, by ‘developmental window’ we do not mean a ‘sensitive’ or ‘critical’ period, but are simply highlighting the period between when right left asymmetries are and are not clearly evident in relation to arm movements with and without a toy present.
Second, the rapid emergence of hand asymmetry over the first few months after reach onset suggests infants are experiencing comprehensive developmental changes akin to a system wide ‘reorganization.’ Thus, it is important to acknowledge the range of developmental changes occurring intrinsic and extrinsic to the infant above and beyond reaching and grasping, many of which also exhibit asymmetrical features. For example, head and trunk postural control is rapidly changing and is linked to arm and hand control before and after reach onset (Carvalho, Tudella, & Savelsbergh, 2007; Michel & Harkins, 1986; Rochat, 1992; Van der Fits et al., 1999). Studies in children with developmental delays further exemplify that hand dominance is influenced by both intrinsic and extrinsic factors (Corbetta, Williams, & Snapp-Childs, 2006; Washington et al., 2002). An important yet rarely studied factor that changes significantly during early infancy is the physical and social interactions between caregiver and infant (Fogel, Messinger, Dickson, & Hsu, 1999). Several human and animal studies have suggested that caregivers may be providing objects, play activities, and maternal cradling in such a way as to influence asymmetrical infant behaviors (Bourne & Todd, 2004; Fagard & Dahmen, 2004; Harkins & Michel, 1988; Michel, 1992). Lastly, a multifactorial approach must also consider the interaction of multiple skills. For example, infants gaining sitting skill increasingly shift away from using bilateral arm support to unilateral support, which in turn may reinforce the use of one arm for stabilization and one hand for object exploration. Even after reaching and in the presence of stronger extrinsic constraints, infants may not exhibit stable right–left differences until they “solve higher level perceptual motor processes” (Corbetta & Thelen, 1996, 1999; Corbetta, Thelen, & Johnson, 2001; Thelen et al., 1993).

Limitation and Conclusions

Given that this is the first longitudinal study of right–left differences in pre-reaching movements, there were several limitations to our conclusions. First, our infants sat with their trunks supported in a custom chair interacting with an adult sitting in their midline that either spoke to them or offered them a stationary midline toy. Such a ‘midline oriented’ environment, trunk support and/or sitting position may have resulted in atypically high levels of symmetry compared with when infants are supine, or held by a parent. Second, our results were based on averages for each pre-reaching week. Development of asymmetry may well be occurring on other time scales such as the seconds to minutes within a series of trials (Corbetta & Thelen, 1999; Newell et al., 2001; Thelen et al., 2000). Lastly, our results focused on one small behavior of the arms. Early infancy is a time of system wide lateralization including object exploration (Barrett, Davis, & Needham, 2007; Ruff, 1984), hand-mouth behaviors (Xue, Zartarian, Moya, Freeman, & Beamer, 2007), leg movements (Pieck et al., 2002), and tongue movement (Sheppard & Mysak, 1984). The developmental origin of hand dominance ultimately reflects the interplay of asymmetries across multiple time scales, levels of organization, contexts and infant behaviors. Future studies can now further test these specifics to determine if there is a comprehensive lack of right–left differences in pre-reaching movements.

NOTES

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