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What is the role of infant banging in the development of tool use?

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Abstract

Throughout the first year, infants are known to engage in repetitive motor behaviors. The current study examines the changes in the hand-trajectory of one such behavior, banging, during the second half-year and the implications of these changes for tool use development. Fourteen (7- to 14-month-old) infants were seated at a table and presented with a small wooden cube. Kinematic measurements of their banging movements were recorded at 240 Hz. Analyses revealed stable temporal characteristics of the hand trajectories within and across infants. Results further indicated that as infants became older, their hands moved more efficiently in straighter up and down trajectories, with developmental changes especially pronounced for upward excursions of the hand: Younger infants' arm movements were less straight on the way up than down, but there was no difference in the straightness of the two movement phases for older infants. These changes with age may reflect improvements in overcoming constraints associated with gravity and/or in motor planning. Additionally, the angle at which infants hit the table became more perpendicular with age. Collectively, the reported changes lead to more efficient movements, better aim and improved force delivery, enabling spontaneous banging movements to become well suited for instrumental hammering and tool use, more generally, later in childhood.

Keywords

tool use; motor development; infancy; banging; motor control

Introduction

How do developmentally earlier behaviors give rise to skilled action? In the study of human locomotion, researchers have investigated the role that neonatal stepping and kicking reflexes play in how infants learn to crawl and walk (Thelen and Ulrich 1991). Similar questions surround the influence of early movements of the upper extremities on the development of manual skill in infancy. Yet compared to detailed research on the relation between early motor behaviors and locomotion, much less is known about corresponding issues concerning manual skill development. In particular, it is not clear what role earlier appearing manual behaviors play with regard to the emergence of later adaptive actions, including those involved in tool use.

During the first year, infants are known to engage in a large number of spontaneous movements (Piek and Carman 1994). These movements do not have an apparent goal and are evidenced by all four limbs, the torso and the head. A subset of these spontaneous movements has been termed rhythmical stereotypies (Thelen 1981) because they frequently

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occur in bouts where they are repeated numerous times in close succession, although they regularly take place in single instances as well. These behaviors appear frequently in the first year and in some instances they resemble and closely precede movements that we would recognize as skilled actions. This insight has led Thelen and other researchers to hypothesize that these behaviors constitute an early action repertoire that infants subsequently adapt for later forms of skilled activity (Goldfield 1995; Lockman 2000; Thelen 1981).

Thelen and colleagues have studied the execution of supine kicking, stepping reflexes and later locomotion at the motor level (Thelen and Fisher 1982; Thelen and Ulrich 1991). The results show that the same motor patterns are evident in both, lending support to the idea that early motor behaviors are indeed recruited for later instrumental ends. In a similar vein, we propose that the foundations of the actions that are employed in common forms of manual tool use can be found in the arm and hand movements of infants.

Compared to the fine-grained studies on locomotion, however, there has been far less work concerning the development of any of the repetitive manual behaviors exhibited by infants (Piek and Carman 1994). These behaviors are typically evident later in development relative to the lower extremities and peak in the second half-year and include waving, slapping and banging movements (Thelen 1979; 1981). By repeatedly performing these behaviors, infants gain practice in control (Sporns and Edelman 1993), enabling these behaviors to be deployed successfully in situations where some form of instrumental action is required.

To understand how an early manual behavior may transition to an instrumental and more controlled form of action, it is necessary to describe developmental changes in the form of that action. To date, however, descriptions of common infant manual behaviors other than reaching have largely been based on observations in terms of frequency of occurrence and have lacked detailed information about changes in movement parameters. Such information, however, may be relevant for understanding the emergence of more controlled forms of action, including tool use.

To address this issue, we focused on the developmental changes in object banging. Object banging is of particular interest for understanding the development of tool use because it shares many features with percussive behaviors that are performed by both humans and non-humans when employing tools for hammering or pounding (Liu et al. 2009; Resende et al. 2008). Additionally, infants devote a considerable amount of time to banging objects and the energy costs can be substantial. Yet, the benefits of this early and significant investment of time and energy are not well understood. We suggest that one benefit for infants is that this behavior serves as a precursor to the actions that they will subsequently employ during basic and everyday forms of tool use. For banging to transition to effective tool use, however, the developmental changes at the motor level must be advantageous with regard to the aim of the hand and efficient force delivery. We investigated these possibilities by presenting infants with cubes and studied developmental changes in the motor organization of their spontaneous banging with high-speed kinematic recordings, focusing on changes in parameters relevant to tool use.

Method

We tested fourteen infants (7 males) between the ages of 7 - 14 months (mean = 312 days, sd = 65 days). Previous research has shown that infants most frequently engage in banging movements during most of this age range (Palmer 1989; Piek and Carman 1994; Ruff 1984; Thelen 1981). Infants came to the lab for a single session lasting about 15 minutes. Infants' movements were recorded using one video camera at 30 Hz (Sony HandyCam) feeding the video stream directly to the motion capture software. Kinematic measures were recorded

using eight Qualisys ProReflex240 cameras at 240 Hz. Eleven passive reflective markers were placed on the infants' upper bodies with hypoallergenic tape (see Figure 1). One marker was placed at the Xiphoid Process (Sternum) and five on each arm at the following locations: Acromioclavicular (Shoulder), Lateral Epicondyle (Elbow), Radial Styloid (Wrist), Ulnar Styloid (Wrist) and 3rd Metacarpal (Knuckle). The marker placement is a simplified version of that suggested by Wu et al. (2005).

During the study, infants were seated on their parents' laps in front of a tabletop surface. Parents were asked to hold infants around the hip to provide a stable base of support while also allowing infants free range of motion of the upper body. Infants were presented with a 2.5 cm (1 inch) cube in order to elicit banging behaviors, but were otherwise allowed to explore the tabletop surface freely. Testing ended when the infant became fussy or had lost interest in the task.

Banging usually occurred in bouts, which we broke down into individual strikes for our analyses. The median number of strikes per bout was 3, and the range was from 1-26 strikes. The number of strikes per bout was not correlated with age ($r_{64} = -.07$, $p = .59$). The beginning and end of each strike were determined based on the kinematic data. Specifically, they were defined as the time points when the hand began and stopped moving vertically. All strikes were defined as uninterrupted up and down movements of the hand so that the cube/hand was contacting the table at the beginning and end of each strike. Taken together, the fourteen infants produced 300 strikes of banging the cube on the table.

Results

To investigate whether banging becomes pre-adapted for tool use, we focused on variables describing the possible aim and force delivery of the object hand. Specifically, we asked whether infants moved their hands straight up and down, at what angle their hands hit the table surface and what the velocity profile of their hands is during banging. We broke down each single strike into its upwards and downwards components. We defined the peak of each strike as the single frame (@ 240 Hz) when the hand reached its maximum height. The upwards phase was then defined as all frames from the beginning of the strike to the last frame before the peak. Similarly, the downwards phase was defined as all frames from the first frame following the peak to the conclusion of the strike.

All analyses were done using mixed-effects modeling using the nlme library in R (Pinheiro and Bates 2000). While no two infants were of the exact same age, several infants were only several days apart at the time of testing. Since any differences between the means of two such infants would inherently be classified as error variance, we included a random effects term for each participant to address differences in development at similar ages. We further explicitly modeled variance as a function of age to test whether infants were becoming more or less variable as they got older. We chose the function $\sigma^2 = \text{age}$ to model the dependence of the variance on age. If $\sigma^2 = 0$, there is no relation between variance and age, if $\sigma^2 > 0$ variance increases with age and if $\sigma^2 < 0$ variance decreases with age. Heteroscedasticity is defined as unequal variance of the regression error terms at different values of the IV. Due to the random effect for participants, the error term for these models can be seen as an indicator of within subject variance. The formal hypothesis test for heteroscedasticity is no different from other significance tests. Since σ^2 needs to be estimated from the data, one parameter is added to the model and the improvement in log-likelihood between the basic and heteroscedastic model is evaluated against a χ^2 distribution with one degree of freedom.

Straightness Ratio

The first variable we computed to analyze movements of the hand is the straightness ratio. Previous research on reaching has shown that infants move their hands in straighter trajectories to a target as they get older. It is unclear, however, if such improvements in efficiency also occur in banging. The straightness ratio was computed as the overall distance traveled by the hand divided by the vertical distance the hand traveled for a given strike. A ratio of 1 in this case would indicate that the hand moved in a perfectly straight line upwards and downwards, while a high ratio would indicate a lot of sideways and forwards movements of the hand. Adults who were asked to bang showed a straightness ratio close to 1.

We regressed straightness ratio onto age. Results revealed a significant decrease in the straightness ratio ($b_{\text{Age}} = -.001$, $t_{12} = -2.53$, $p < .05$), indicating that as infants get older their hands move more along a straight up/down line (see Figure 2). Several of the younger infants deviated significantly from straight vertical hand trajectories, while none of the older infants did so. The analysis also revealed significant heteroscedasticity ($\chi^2 = 2.12$, $df = 1$, $p = .147$), meaning that the amount of variance decreases significantly with age.

In a follow-up analysis we separated each strike into its upward and downward phase and computed a straightness ratio for each phase separately. We then entered age, phase and the age $\times$ phase interaction into a mixed-effects model to predict the straightness ratio. Phase was coded as a binary variable with upward coded as zero and downward as one. The analysis yielded significant effects for age ($b_{\text{Age}} = -.001$, $t_{12} = -3.23$, $p < .01$), phase ($b_{\text{Phase}} = -.26$, $t_{12} = -3.97$, $p < .01$) and the age $\times$ phase interaction ($b_{\text{Age} \times \text{Phase}} = .0006$, $t_{12} = -3.46$, $p < .01$). Figures 3a & 3b show that as infants get older, they move their hands in straighter trajectories. Furthermore, the age by phase interaction indicates that the increase in straightness with age (decrease in straightness ratio) is significantly greater for the upward than downward movement of the hand: the predicted value of the straightness ratio for a 7-month-old infant is 1.37 for the upwards phase and 1.24 for the downwards phase, but for a 14-month-old the predicted straightness ratio is equal for both phases at 1.13.

Angle of Impact

The second variable we analyzed has direct implications for the efficient delivery of force when banging. We examined the angle of impact of the cube-in-hand against the table surface. We computed this angle based on the plane of the table and the directional movement vector of the hand during the last 50 ms (12 frames @ 240 Hz) immediately prior to the cube striking the table. The movement vector was computed by subtracting the position of the hand 50 ms prior to impact from the final position of the hand. An angle of 90° would mean that the hand is coming down perfectly perpendicular to the table surface. Thus the closer the angle of impact is to 90°, the higher the percentage of force that will be delivered directly downward. We regressed the angle of impact onto age. Results showed a significant effect of age ($b_{\text{Age}} = .05$, $t_{12} = 2.61$, $p < .05$) and no significant heteroscedasticity. As infants get older, the average angle of impact increases (Figure 3c), suggesting that force delivery is becoming more efficient with age.

Velocity

To investigate the velocity profile of the hand during banging we focused on three variables: peak velocity, the timing of the peak velocity and the velocity at impact. Previous research on early reaching reported that young infants' hand movements consist of several sub-movements, each with its own acceleration, deceleration and velocity peak (von Hofsten 1979). Our data on banging movements, in contrast, revealed only a single acceleration and

deceleration during each upwards and downwards phase, resulting in one peak velocity for each of phase.

Peak velocity was entered into an age x phase mixed-effects model, results showed a significant effect of phase ($b_{\text{Phase}} = 6.85$, $t_{12} = 6.08$, $p < .01$), but not age. Not surprisingly, peak velocity during the downwards phase ($M = 11.05$ m/s, $SD = 4.56$) was significantly higher than peak velocity during upwards phase ($M = 6.05$ m/s, $SD = 2.38$). To analyze when peak velocity was achieved in each movement phase, we time-normalized the upwards and downwards phase separately for each child such that each phase consisted of 100 frames. Time was thus analyzed as a percentage of the duration of each up or down trajectory. Time of peak velocity was entered into an age x phase mixed-effects model. A significant effect of phase emerged ($b_{\text{Phase}} = .21$, $t_{12} = 4.88$, $p < .01$), but not for age. For the up phase, peak velocity occurred after the hand had traversed 56% of its total upward movement. In contrast, for the down phase, peak velocity occurred significantly later after the hand had already traversed 71.1% of its total downward movement (see Figure 4). It is worth noting that the peak velocity of the downward strike did not occur at the conclusion of the strike. Instead the final velocity with which infants hit the table was on average 8.47 m/s, or 74.8% of peak velocity.

Discussion

The present findings suggest that banging transitions in the second half-year into a form of manual behavior that is well suited for tool use—even before infants have obtained much experience with hammers or other pounding instruments. Just as early kicking serves as a substrate for the emergence of human locomotion (Thelen 1981; Thelen and Fisher 1982), we suggest that early object banging serves as a substrate for the later emergence of percussive behaviors that are employed for tool use.

In particular, the changes we observed in the spatial characteristics of the hand-trajectory across the second half-year during banging enable better aim and force delivery. Moving the hands in straighter up and down trajectories is more efficient than moving in circuitous paths and also provides infants with the best opportunity to aim their strikes at possible targets. In consequence, this allows infants to keep their hands almost directly over the area they will strike during the entire movement. Bringing down the hand in a more perpendicular trajectory enables infants to deliver most of the force onto the object they strike. By contrast, more acute angles of impact would lead to large percentages of potential force being directed sideways. Another consequence of delivering force straight downward is that glancing blows are easier to avoid when bringing the hand down in a straighter fashion. In sum, these developmental changes make banging movements more efficient and useful for instrumental ends.

There are several possibilities why these changes are especially pronounced during the upwards phase of the movement. One possibility is that motor limitations at the young ages are more noticeable when infants are working against gravity rather than with it. Gravity exerts its force directly downward and therefore may lead infants to move their hands straighter during the downwards phase. Another possible explanation, though not mutually exclusive, is that advances in motor planning at the older ages underlie the changes. Younger infants may attempt to simply bring the hand up without regard to its exact trajectory and focus mainly on the downward phase — when they are actually hitting the table with the object and creating noise. In contrast, older infants may be planning the movement as a whole, integrating both phases into a single motor plan for banging.

Our analysis of the temporal characteristics of the hand movements revealed significant differences between the upwards and downwards phases of the movement and also high degrees of stability both within and across infants. In addition, the exact timing of the peak velocity during the upwards phase is notable because it resembles velocity profiles that adults show when reaching for a similar size cube (Bootsma et al. 1994). Both adult reaching and infants' hand movements during banging begin and terminate at rest, consist of a single acceleration and deceleration phase and attain peak velocity shortly after the temporal midpoint of the movement. Thus during the upwards phase, infants at all ages are displaying a stable temporal pattern of arm and hand movement that resembles that of skilled reaching movements in adults. The timing of peak velocity during the downwards phase is also noteworthy since infants do not contact the table with the object at peak velocity, but rather at 75% of peak velocity. Nevertheless, the current data do not allow us to differentiate between the possibilities that infants are volitionally braking their movements versus a more passive scenario where stretch receptors in the arm's musculature slow down the movement before completion.

The developmental pattern we observed between 7 and 14 months provides insight into the exact nature of the changes that infant banging undergoes as it becomes pre-adapted for tool use. While the temporal characteristics of banging appear stable, infants show clear changes in the spatial features, especially during the upwards phase of the movement. We believe that the reported gains in the control of banging are not likely due to experience with any actual tools because infants generally begin using percussive tools well after one year of age (Gesell 1940). Rather, banging appears to become pre-adapted for tool use, possibly due to the experience that infants gain by spontaneously and repeatedly producing this behavior on their own. As a result, older children will be able to evidence a more controlled, skilled and efficient form of percussive action. More broadly, these findings suggest that percussive tool use in humans develops gradually, paralleling what developmentally occurs in non-human primates as they attempt to learn how to use a hammerstone to crack open a nut (Inoue-Nakamura and Matsuzawa 1997).

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Figure 1. One of the infants from the study while banging. The placement of all 11 markers is illustrated by the black dots.

Figure 2.

The axes of both graphs are measured in mm. Depicted are hand trajectories (the marker is placed on the knuckle of the middle finger) for the first 5 strikes of a 214 days old infant a) and a 408 days old infant b). All strikes were standardized to begin at the Cartesian origin. The figure illustrates the curved hand trajectories seen at younger ages and the straighter up-and-down trajectories typical of older infants.

Figure 3.

The figure shows all of the individual data for each strike (o) and the regression line for each analysis. No two infants were of the exact same age so the data at any given age come from a single infant. Figure a) depicts the straightness ratio during the upwards movement of the hand while figure b) depicts the same for the downward movement. Figure c) shows the angle at which the hand strikes the table surface. The angle is computed between the movement vector of the hand during the last 50 ms before contacting the table and the table surface. Angles near 90° indicate the hand coming down perfectly perpendicular to the table while lower angles are indicative of more acute approach.

Figure 4.

The figure shows the mean and standard error of the point in time when infants' hands reach peak velocity for all of the strikes that were collected from each infant. Figure a) refers to the upwards movement of the hand, infants on average reached peak velocity at 56% and the average intra-infant standard error is 3.7%. Figure b) refers to the downwards movement of the hand, infants on average reached peak velocity at 71% and the average intra-infant standard error is 1.9%.