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When does tool use become distinctively human?: Hammering in young children

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Abstract

This study examines the development of hammering within an ontogenetic and evolutionary framework using motion-capture technology. Twenty-four right-handed toddlers (19–35 months) wore reflective markers while hammering a peg into a peg-board. The study focuses on the motor characteristics that make tool use uniquely human: wrist involvement, lateralization, and handle use. Older children showed more distally controlled movements, characterized by relatively more reliance on the wrist, but only when hammering with their right hand. Greater age, use of the right hand, and more wrist involvement were associated with higher accuracy; handle use did not systematically change with age. Collectively, the results provide new insights about the emergence of hammering in young children and when hammering begins to manifest distinctively human characteristics.

Hammering and, more generally, percussive behavior are staples of the human tool kit. Perhaps due to its prevalence in humans and appearance in several other non-human primates, percussive tool use has been the subject of research interest across anthropology (Schick & Toth, 1993; Semaw, 2000; Stout & Chaminade, 2007), primatology (Inoue-Nakamura & Matsuzawa, 1997; Liu et al., 2009; Resende, Ottoni, & Fragaszy, 2008), and motor behavior (Biryukova & Bril, 2008; Bril et al., 2012). Yet, despite interest across these diverse fields, very little is known about the ontogeny of percussive tool use in humans. Past studies on children's tool use have largely focused on the selection of an appropriate tool (Brown, 1990; Chen & Siegler, 2000; Klatzky, Lederman, & Mankinen, 2005), without addressing developmental changes in the use of that tool. In contrast, in the present study we examine tool *using* and focus on developmental changes in how young children begin to employ hammers. In doing so, we ask when in development does hammering begin to manifest qualities that might be considered uniquely human.

Research on percussive tool use across non-human primates and human adults reveals several important findings that can guide questions about the development of percussive tool use in children and its uniquely human character. First, across non-human and human primates, change in tool use proficiency appears to be gradual (Bril, Rein, Nonaka, Wenban-Smith, & Dietrich, 2010; Inoue-Nakamura & Matsuzawa, 1997). Second, relative to non-human primates, the human wrist is unique and heavily involved in percussive tool use (Biryukova & Bril, 2008; Boesch & Boesch, 1984; Liu et al., 2009; Marzke, 2009). Finally,

only in humans is manual lateralization at the population level a defining feature of highly skilled motor behaviors, such as tool use (McGrew & Marchant, 1996).

Gradual Emergence of Tool Use

The last common ancestor of humans and other great apes, 5–8 Million years ago, was most likely already a tool user with a similar skill set to modern chimpanzees, engaging in behaviors such as pounding rocks on anvil stones and using sticks for termite fishing (Panger, Brooks, Richmond, & Wood, 2003). The first conclusive change from these early tool using behaviors comes from evidence of hominid tool making around 2.5 million years ago (Semaw, 2000). Tool making in this era was characterized by direct percussion flaking -- a technique where a hammerstone is repeatedly used to strike a block or cobble in order to chip away flakes of stone to create a desired shape. Tools became slightly more complex over the next 2 million years, yet the basic manufacture and use of tools remained much unchanged (Ambrose, 2001). Only toward the end of the Middle palaeolithic age, lasting from 300,000 – 30,000 years ago, does the archeological record show a proliferation of tool manufacture and use. Thus for much of history, human percussive tool use was akin to that of non-human primates, but gradually growing in complexity.

From an ontogenetic perspective, percussive tool use in non-human primates appears to unfold gradually as well. Chimpanzees in the wild require several years of practice to master the use of stone anvils and hammers when attempting to open nuts (Inoue-Nakamura & Matsuzawa, 1997). Juvenile chimpanzees start to use stones and anvils by 1.5 years of age and perform many of the actions necessary for tool use, but assembling all of the action components of percussive tool use and developing the necessary aim and control of force takes the chimpanzees an additional 2–2.5 years. A similarly prolonged period of development for nut-cracking can be observed in capuchin monkeys (Resende et al., 2008).

Examining the time course for human adults to become proficient tool users reveals a similarly protracted pattern of improvement. In studies on stone knapping, experts tend to be far more efficient in their movements and produce larger flakes with less energy expenditure relative to novices (Bril et al., 2010). Developing this high level of expertise can take years, however. For instance, in a study comparing stone knappers with different levels of expertise, only those with more than 20 years of active experience were consistently able to predict the size and shape of the stone flakes that they produced (Nonaka, Bril, & Rein, 2010).

Research on the neural underpinnings of tool use is also consistent with the idea that tool use is acquired gradually. Current theory holds that a tool can become incorporated into the neural schema of the body, allowing the brain to treat the tool as a physical extension of the body (Maravita & Iriki, 2004). Based on research with non-human primates, this process takes hundreds of repetitions over long periods of time, supporting the idea that tool use learning is a long and gradual process (Hihara et al., 2006; Iriki, Tanaka, & Iwamura, 1996; Ishibashi et al., 2002).

At an ontogenetic level, research also indicates that tool use emerges gradually (Kahrs, Jung, & Lockman, 2012; 2013). As infants gain practice when banging objects during the second

half year, their percussive arm movements become more uniform, efficient and straight and deliver more consistent levels of force. These changes suggest that during the second half-year, banging gradually transitions into a behavior that is pre-adapted for percussive forms of tool use. More broadly, these bodies of work indicate that in humans, the development of tool use involving percussive behavior requires an extended period of time for the motor control associated with this skill to emerge.

Involvement of the Wrist in Percussive Tool Use

Despite the similarity between percussive tool use in humans and some non-human primates, there are also notable differences in tool use between these species at a motor level. Chimpanzees rely almost solely on the shoulder and elbow when cracking nuts (Boesch & Boesch, 1984), while capuchins use a technique akin to that of human powerlifting – raising stones over their heads using the musculature of their legs, torso and arms throughout the movement (Liu et al., 2009). Importantly, neither species relies on the wrist when engaging in percussive tool use, which is precisely what humans do. Involvement of the wrist is especially useful in precision tasks, in part, due to the wrist's distal position and smaller musculature (e.g., consider attempting to write with a pen while controlling the movement primarily from the shoulder). Throughout the evolutionary record, wrist and hand morphology are closely intertwined with the complexity of tool use and tool production in different species (Marzke & Marzke, 2000; Tocheri, Orr, Jacofsky, & Marzke, 2008). In contrast to non-human primates, the modern human wrist and hand are specialized for flexibility, dexterity and forceful grips that in combination make it perfectly suited for percussive tool use (Marzke, 2009). As a result, skill levels in non-human primates do not reach the level seen in humans even with the opportunity for extended practice. Illustratively, although the chimpanzee Kanzi practiced using a hammerstone to produce flakes for many years, he never approached the level of skill seen in humans (Toth et al., 1999), presumably because his wrist morphology prevented him from ever achieving proper mastery. Furthermore, early archaeological artifacts from 2.5 million years show that even early hominids were far more skilled at stone flaking than Kanzi.

The importance of the wrist becomes even more apparent when individuals use tools with handles. Research with human adults on the mastery of stone knapping with mallets has found that the greatest angular change (Biryukova & Bril, 2008) and joint acceleration (Côté, Raymond, Mathieu, Feldman, & Levin, 2005) amongst the hand and arm joints occur in the wrist. Potential kinetic energy is directly related to the velocity of the hammer head at the point of impact (Biryukova & Bril, 2008) and the highest wrist acceleration, quite literally a snapping of the wrist, tends to occur at the end of the downwards swing, being preceded by the peak acceleration of the more proximal joints of the shoulder and elbow (Williams, Gordon, & Richmond, 2010). In human adults, the wrist thus controls to a great degree the amount of force that is imparted, while its distal position also allows for greater precision than movements relying on the elbow or shoulder.

Manual Lateralization

A final aspect of tool use that separates human from non-human primates is manual lateralization. In many instances of human tool use, distinctly different demands are placed on the two hands, one hand often guiding the tool and the other supporting or steadying the object to be acted upon. Modern humans are generally right handed (90%), and the preference to use the right hand is strongest in precision tool use. According to estimates based on the archaeological record, humans around 1.9–1.4 million years ago were already right handed at the population level (Toth, 1985). Moreover, it has been proposed that the differential roles of the hands during tool making were in fact a driving force of the evolution of lateralization in humans (Ambrose, 2001), suggesting that advanced tool use, wrist morphology and lateralization are inextricably linked with one another. Nevertheless, little is known about the development of lateralization during ontogeny in the context of percussive tool use in humans.

Current Study

The current study is one of the first investigations of joint movements during manual tool use in young human children. We examine the emergence of hammering during the period roughly spanning 1.5 – 3 years of age, when children begin to use hammers. Based on the preceding discussion, we focus on unique specializations associated with human hammering: developmental changes in the role of the wrist, differences between the preferred and non-preferred hand, and use of the handle. To address these issues we employed kinematic methods and tracked the movement of the torso, each upper limb and the hammer with high-speed motion capture cameras.

Method

Participants

The final sample consisted of 24 right-handed children, consisting of 12 males (ranging from 19 to 35 months of age, $M = 28.7$, $SD = 3.47$) and 12 females (ranging from 20 to 34 months of age, $M = 27.9$, $SD = 3.60$). Participants were recruited from local preschools in a metropolitan area and from responses from online community advertisements. The families of the participants were primarily Caucasian and middle class (20 Caucasian, 2 African American, 1 Hispanic, 1 Asian). Children received a small toy for their participation. An additional 17 infants were tested, but due to fussiness or their removal of some of the infrared markers from their bodies, 14 of these children did not provide enough data to be included in the analysis. The remaining three children were reported to be left-handed by their parents and were therefore excluded.

Apparatus & Procedure

Children were seated at a table (62 cm × 122 cm × 67 cm) and were asked to use a small wooden toy-hammer to drive a single peg all the way into a pegboard (see Figure 1). The pegboard was glued to a wooden surface that was inserted into an opening in the table surface to prevent the apparatus from sliding during the task. If children did not engage in the task after repeated requests, the experimenter would demonstrate driving the peg into the

pegboard once. Children were presented the hammer to either the right or left hand and the task was repeated four times with each hand in randomized order. Children were instructed to use only one hand at a time and rest the other hand on the table surface. The requirement to keep the free hand resting on the table was a consequence of pilot trials in which children would often try to switch the hammer from one hand to the other when being asked to use their non-preferred hand.

In order to track movements of the hand and hammer, reflective markers were placed on both. To place markers on children's hands, the experimenter used double-sided surgical tape and placed one marker on the sternum (Processus Xiphoideus), one on each shoulder (Art. Acromioclaviculare), one on each elbow (Lateral Epicondyle), two markers on the child's wrist (Radial Styloid and Ulnar Styloid), and one on the knuckle of each of the child's middle finger (3rd Metacarpal). This marker placement is a simplified version of that suggested by Wu et al. (2005). Three markers were also placed on the head of the hammer to enable a full three dimensional reconstruction of the hammer's position throughout each trial (see Figure 1). Kinematic data were recorded at 240Hz using eight infrared cameras (Qualisys ProReflex240) positioned in a semicircle around the front of the table. A video-stream from a Sony HandyCam at 30 Hz was fed into the Qualisys software for time-synchronized recordings of both kinematic data and regular video.

Handedness

Parents filled out the Edinburgh Handedness Inventory (Oldfield, 1971) to identify the degree of right- and left-handedness for each child. The score ranged from -2, strongly left handed to +2, strongly right handed, for each item. The mean score across items for the group was 0.91. Twenty two children had average scores higher than zero indicating a right-hand preference. Two children were reported to have no discernible hand preference. The results reported in this study include the right-handed children and those who did not have a hand-preference (When the analyses included the right-handed children only, the findings were identical to the ones reported below.)

Kinematic Data Analysis and Computational Methods

Each trial consisted of multiple strikes and was subsequently divided into single strikes that serve as the basis for all analyses. The video was consulted to determine when a strike had occurred. The exact starting and ending points of each strike were subsequently determined from the kinematic data and defined as the points when the hammer began (or stopped) moving vertically.

The trajectories for all markers were identified with the Qualisys software (QTM Track Manager) and then exported to MATLAB for further processing. Any missing data were interpolated using a cubic spline. To reduce measurement error, trajectories were then smoothed using a least squares spline approximation. Joint angles were computed based on the procedure of Grood & Suntay (1983). Hammer movement and velocities were also computed in MATLAB as was hand to hammerhead distance. This measure was defined as the distance between the knuckle of the middle finger and the distal plane of the hammerhead (in mm).

Three of our measures were coded visually from the recorded video: looking behavior, strike outcome, and trial outcome. Looking behavior was coded as looking or not looking. Children's visual attention rarely changed within a single strike, however, when this occurred looking behavior was determined based on whether children were looking on more than half of the duration of the strike or not. Strike outcome was coded as full hit, partial hit or miss. If children hit the top of the peg and the hammerhead remained on the peg throughout the contact strikes were coded as a hit. If children hit the top of the peg with a glancing blow or made partial contact with the top-edge, strikes were coded as partial hits. Strikes where no contact with the top of the peg occurred were scored as misses. Lastly, trial outcomes were scored as fully driving the peg in or failing to do so. If the bottom of the peg was touching the table surface at the end of the trial it was scored as a success. Twenty percent of the sample was double-coded and inter-rater agreement for these variables was on average 95% (range: 91% – 100%). Adjusting for chance agreement using Cohen's Kappa resulted in a range of Kappa from .87 to 1.

Results

All analyses were run in R (2012) using a mixed-effects model with a random intercept for each participant (Pinheiro & Bates, 2000) or Generalized Estimating Equations (GEE) when looking at binary outcome variables (e.g., success in driving in the peg on a trial). Both techniques are able to account for the non-independence of our data stemming from the repeated measurements of each child. Children were asked to complete four trials (each trial consisted of multiple strikes and ended when the child had driven the peg entirely into the peg board or ceased to attempt any further strikes) with each hand; however, only one child under the age of 750 days attempted any trials with the left hand. The other children under 750 days of age ($N = 4$) refused to use their left hand, but readily used their right hand. Because only one child used the left hand under 750 days of age and therefore might unduly influence any regression concerning hand-use, we chose to remove the left hand data of this child and focus instead on children older than 750 days for all analyses of left handed hammering. Two older children did not yield any data with their right hands due to fussiness. Our left hand data thus range in age from 750–1053 days ($N = 17$), consisting of 47 trials and 396 strikes. Our right hand data range from 584–1053 days ($N = 22$), consisting of 76 trials and 421 strikes.

Trial Analyses

Successful completion of trials—Success on each trial was coded as a binary variable based on whether the child managed to drive the peg all the way into the board. Using GEE, success was regressed onto a full factorial of age and hand-used. Significant main effects of age ($b_{Age} = 0.007$, $\chi^2_1 = 6.79$, $p < .01$) and hand ($b_{Hand} = 1.19$, $\chi^2_1 = 5.25$, $p < .05$) were found. Figure 2 shows the predicted success rates based on age and hand. Children became more successful at completing the task as they got older and throughout the entire age range, they were significantly more successful when using their right hands.

Number of strikes per trial—Next, the number of strikes (regardless of hitting the peg or not) per trial was regressed onto age, hand and trial success using mixed-effects modeling. A

significant main effect of hand ($b_{Hand} = -2.34$, $F_{1,98} = 10.7$, $p < .01$) was found. On average, children made 5.54 strikes when using their right hand and 8.43 strikes per trial when using their left hand. The main effect of hand also emerged when considering successful trials only ($p = .04$).

Individual Strike Analyses

The next set of analyses center on individual strikes and focus on looking behavior, effects of the grip location on the handle, joint movement parameters, successfully striking the peg and adjustments children made after misses.

Looking—Across the 123 trials, children attempted 817 (421 right handed) strikes. Looking behavior was coded as either “looking” or “not looking” for each individual strike. Looking behavior was then regressed onto a full factorial of age and hand using GEE. A significant effect of age emerged ($b_{Age} = 0.01$, $\chi^2_1 = 12.50$, $p < .001$), indicating that children looked on a greater percentage of their strikes as they were getting older. While children at the youngest ages were only looking about 50% of the time when they were hammering, children at the oldest ages were almost always looking during a strike (see Figure 3).

Strike hits—Of the total 817 strikes, children fully hit the peg 72.3% of the time, missed it 17.5% of the time and made partial or glancing strikes 10.2% of strikes. Because glancing blows were relatively infrequent and could be considered as either partial hits or partial misses, they were not included in the following analyses.

Using GEE, we examined whether a full hit of the peg was predicted by age, hand used and looking behavior. Results revealed a significant effect of looking ($\chi^2_1 = 11.26$, $p < .001$) and hand used ($\chi^2_1 = 4.40$, $p < .05$), while the main effect of age approached significance ($b_{Age} = .003$, $\chi^2_1 = 3.14$, $p = .077$). These results indicate that children were more successful when judged to be looking at the pegboard (83.4% when looking and 43.4% when not looking) and when using their preferred right hand (82.9% and 77.9%, respectively). However, they only showed a tendency to improve with age in fully striking the peg after controlling for the increase in looking, suggesting that developmental changes in the accuracy of children’s hammering in the toddler years can in part be attributed to improved visual attention.

Grip distance—In the next set of analyses, we directly examined how children used the handle of the hammer on individual strikes. The analyses focused on where children gripped the handle in relation to the hammer’s functional end (i.e., the hammerhead) and whether the gripped location changed as function of age and influenced other movement parameters. Although, grip distance did not change systematically with age or hand used ($ps > .05$), it did have pronounced effects on how much the wrist joint moved ($F_{1,788} = 52.95$, $p < .001$). The mean amount of wrist movement when children gripped the hammer close to the hammerhead was 35.8°; this dropped to only 11.4° when children gripped the handle at the far end from the hammerhead. Additionally, no significant changes as a function of grip distance were found for either the elbow or the shoulder joint ($ps > .05$). Therefore, the effect

of the grip distance was specific to the wrist joint and probably represents an attempt by the children to attenuate the increased difficulty resulting when the functional end of the tool is more distal to the body.

Joint movement—Prior research has shown that while hammering involves wrist flexion and wrist pronation, the two are almost perfectly correlated (Leventhal, Moore, Akelman, Wolfe, & Crisco, 2010). We focus, therefore, on flexion as an indicator of overall wrist movement on individual strikes. Analyses were conducted on the three main joint movements (humeral elevation, elbow flexion and wrist flexion) involved in hammering, investigating effects associated with age and hand (left, right). These three kinds of joint movement were chosen a priori as they are the ones most utilized by adults when hammering (Leventhal et al., 2010).

The total amount of movement for each joint was entered into a mixed effects model and regressed onto a full factorial model of age and hand. A significant main effect of hand ($F_{1,791} = 53.9, p < .001$) and an Age x Hand interaction ($F_{1,791} = 25.4, p < .001$) emerged for the wrist joint and the shoulder joint ($F_{1,791} = 10.5, p < .005$ and $F_{1,791} = 11.9, p < .001$, respectively) but not the elbow ($ps > .472$). The interactions indicate that involvement of the wrist and shoulder varied as a function of age and hand. When hammering with the preferred right hand, older children relied more on the wrist and less on the shoulder than the younger children (see Figure 4), while this was not the case for the left hand.

We next looked at the relative contribution of each joint to the overall movement, because children varied considerably in the overall amplitude (the difference between the highest and lowest vertical position of the hammer) of their strikes. The average amplitude ranged from as low as 6.7cm per strike for one child to as much as 32.1cm for another. We computed the combined angular change of the shoulder, elbow and wrist for each strike and used this information to determine the percentage of angular change that was due to each joint on a given strike. We regressed this percentage onto age and hand using identical mixed effects models as in the prior analyses. Results show that the relative contributions of each joint followed a similar pattern as that found for the absolute joint movements. Significant main effects of Hand and significant Hand x Age interactions were found for the wrist ($F_{1,744} = 52.0, p < .001$ and $F_{1,744} = 39.2, p < .001$, respectively) and elbow ($F_{1,744} = 58.0, p < .001$ and $F_{1,744} = 6.93, p < .01$, respectively). In addition, a significant Hand x Age interaction was found for the shoulder ($F_{1,744} = 33.5, p < .001$). As is evident in Figure 5, older children show more distally controlled movement when using the right hand. Post-hoc testing revealed that as children became older, the relative use of the wrist increased ($t_{22}=2.99, p < .01$), while relative shoulder use decreased ($t_{22}=-2.36, p < .05$). In contrast, no such pattern was found when children used their left hands ($ps > .05$). Taken together, these findings indicate that hammering is becoming more distally controlled with age when using the right, but not the left hand.

Strike hits: Movement parameters—In the next analyses, we examined which movement parameters involving the joints and the hammer predicted successful strikes (as before, these analyses are based on full hits and full misses). We included looking behavior as a covariate for this analysis. We entered the amount of shoulder movement, elbow

movement, wrist movement, as well as the distance traveled and peak velocity of the hammer into a GEE analysis. Significant main effects of elbow movement ($\chi^2_1 = 7.56, p < .01$), wrist movement ($\chi^2_1 = 5.18, p < .05$) and distance traveled by the hammer ($\chi^2_1 = 11.44, p < .001$) emerged. These results suggest that children who rely on their wrist when hammering are also more likely to strike the peg accurately. In contrast, relying more on elbow movements decreased accuracy. Lastly, moving the hammer a greater distance was associated with lower accuracy (see Figure 6).

Adjustments to missed strikes—Finally, we examined adjustments that children made after failing to hit the peg fully on a previous strike. We only analyzed adjustments on strikes when children were looking at the apparatus since we did not expect any systematic adjustments to occur when children were not paying attention to the task. A GEE analysis regressing the outcome of the current strike on the outcome of the previous strike, with age and hand used entered into the model as covariates, revealed a significant effect of prior outcome ($\chi^2_1 = 87.6, p < .001$). Children were far more likely to hit the peg if they had done so previously as compared to strikes following misses (see Figure 7a).

We next examined how children attempted to adjust their strike after previously missing the peg. The next analysis focused on the same factors that were potential predictors of hit success in the prior analysis – namely, the amount of joint movement of the shoulder, elbow and wrist as well as hammer distance and hammer velocity. For each measure, we computed the difference between the current strike and the preceding strike. We then regressed this difference onto age and the outcome of the preceding strike using mixed-effects modeling. Therefore, these analyses addressed if children would show changes in the involvement of each joint and if they would move the hammer more or less and slower or faster as a function of the prior outcome. No significant effects were found for any of the joint movement measures or hammer distance. The results, however, did show a significant effect of prior outcome on hammer velocity ($F_{1,557} = 10.16, p < .01$). Children would increase the hammer velocity following a hit and decrease the hammer velocity following a miss (see Figure 7b). As is evident from the results reported in the preceding section, this adjustment was only somewhat successful. Children were still hitting the peg far less frequently after misses (57%) than hits (91%).

Summary

Across the analyses, the results indicated that children were more successful at completing the task with increasing age and when allowed to use their (preferred) right hand. Older children also looked at the task more frequently and became more accurate at striking the peg on individual strikes. Additionally, children's movement parameters differed between the younger and older children when using the right hand: older children showed a more distally controlled movement compared to their younger counterparts. This was not evident with the left hand. Furthermore, controlling the strikes from the wrist was shown to aid accuracy while controlling strikes from the elbow was detrimental. As well, the amount of wrist movement was dependent on where children gripped the handle of the hammer. Lastly, children were frequently unsuccessful in attempting to correct movement errors, as accuracy levels were far lower following misses than hits; the only systematic adjustment children

made following misses was to slow down the hammer velocity. Collectively, these findings reveal how children are beginning to use perceptual and motor feedback in attempting to become more skilled at hammering.

Discussion

Following attempts at trying to understand the emergence of percussive tool use in non-human primates (Inoue-Nakamura & Matsuzawa, 1997; Resende et al., 2008), we report some of the first data on early human hammering. Our study drew inspiration from prior research on tool use from anthropology, comparative psychology and neuroscience and attempted to apply findings in these literatures to the domain of human ontogeny. Our larger goal was to address when in development does hammering begin to manifest qualities that might be considered uniquely human.

As noted, one of the cardinal features of manual tool use in humans relative to that of other primate species centers on the role of the wrist. The morphology of the human wrist is unique in its potential for contributing to fine-motor skill in precision tasks (Marzke & Marzke, 2000). The results reported here suggest that the wrist is beginning to take on its characteristic and uniquely human role in skilled manual action between the second and third years. Moreover, in the present sample, the differentiated role of the wrist was only evident in the right hand. While previous research on the early development of manual specialization has focused largely on the frequency, or in some cases straightness, of reaching with one hand or the different roles of the two hands when manipulating objects or using tools (Fagard & Marks, 2000; Ferre, Babik, & Michel, 2010; Hopkins & Rönqvist, 2002; Rat-Fischer, O'Regan, & Fagard, 2012; Rönqvist & Domellöf, 2006), the present results are among the first to suggest an emerging biomechanical signature associated with manual specialization in tool use. Moreover, our findings indicate that the appearance of wrist lateralization is comparably late, especially when considered in relation to other types of manual lateralization (reaching) or specialization (bimanual manipulation) that are evident before the end of the first year.

This developmental sequence may not be accidental. As noted by some investigators, later appearing forms of lateralization may build on earlier appearing ones (Hinojosa, Sheu, & Michel, 2003). Applying this idea here, we suggest that the lateral preference or specialization that appears relatively earlier when infants reach (Ferre et al., 2010) or use the two hands differentially to manipulate objects (Fagard & Marks, 2000) may provide infants with many opportunities to practice engaging the wrist joint of the emerging dominant hand. By virtue of this experience, young children may become better able to control the wrist joint and at the same time, incorporate it into ongoing manual activity.

In a related vein, we suggest that a similarly gradual developmental progression underlies the ontogeny of motor control in percussive tool use. Thelen and colleagues have shown that the early motor patterns involved in infant stepping in the first months of life are recruited for later walking (Thelen, Ulrich, & Wolff, 1991). Similarly, in the context of tool use, we propose that hammering may build on earlier motor patterns that infants use during object banging. Kahrs et al. (2013) reported that by the end of the first year, the underlying

percussive motor patterns of banging change and become well-suited for tool use. One-year old infants have developed sufficient motor control of their proximal musculature to bang objects by using efficient and consistent hand trajectories. Once this form of banging has been achieved, the subsequent challenge for young children engaging in hammering is to adapt these movements to control the tool extending from the hand. In this connection, the present work indicates that developmental changes in the control of early hammering are in large part associated with the increasing role played by the wrist. Relying on the wrist while hammering, in turn, was shown to lead to increased accuracy in striking the peg. The role of the wrist, however, varies in relation to how far the tool extends from the body. In the present study, children were more likely to engage the wrist joint when holding the handle closer to the hammerhead, indicating that they are still in the process of learning how to control this new extension to their body. More generally, the present findings on hammering suggest that, similar to the development of locomotion (Thelen et al., 1991), young children recruit familiar motor patterns and adapt them to new challenges.

It should be noted that the present conclusions refer only to children who were identified as right-handed or did not have a left hand preference. During the course of this study, only three children who were identified as left-handed by their parents were tested. While this number reflects the population level incidence of left-handedness, the small sample size did not allow us to have sufficient statistical power to separately analyze developmental trends for left-handed children. Several studies have shown that left-handed individuals are not simply “like right-handers in reverse” but often seem to be less lateralized (Corballis, 1983). Thus, it is not clear if corresponding developmental findings would be obtained if a large enough sample of young left-handed children were tested.

In conclusion, tool use involving percussive action is seen across a number of primate species (Inoue-Nakamura & Matsuzawa, 1997; Liu et al., 2009), but hammering in children only begins to exhibit its characteristic human form in the third year. By this time, children begin to show relatively greater reliance on their wrists when hammering. Furthermore, in the present sample, this movement pattern was lateralized and involved the right wrist only—mirroring other forms of lateralization that are found at a population level in human tool use (McGrew & Marchant, 1996). The present findings thus suggest that achieving distal control of a percussive tool is a gradual process, spanning the infancy and early childhood years, which builds on earlier action patterns and forms of lateralization. By focusing on developmental changes in the joint movements involved in tool use, we provide new insights into the origins of tool use and its distinctive human character.

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Figure 1.

The apparatus consisted of a toy hammer, peg and pegboard. Eleven markers were placed on the children's arms and torso in addition to three markers on the hammer in order to enable a full kinematic reconstruction of arm and hammer movements.

Figure 2.

The percentages of successfully completed trials (driving peg all the way into pegboard) with each hand for each participant are shown. Children become significantly more successful with increasing age and across all ages children are better when using their preferred right hand. Curve fits are based on a binomial GEE model using a logit link function and regressing success onto age and hand.

Figure 3.

The percentage of strikes during which children were looking at the task and the mean percentage as a function of age (solid line). Each circle represents a single child's percentage of strikes during which they were judged to be looking at the task. Older children looked on a significantly higher percentage of strikes compared to their younger counterparts. The curve fit is based on a binomial GEE model using a logit link function and regressing the probability of looking onto age.

Figure 4.

The average amount of shoulder, elbow and wrist movement across all strikes is shown when using the left hand (a) and the right hand (b). Significant Age x Hand interactions for the wrist and shoulder indicate that with increasing age, children rely more on their wrist and less on their shoulder when hammering with their preferred right hand. The opposite pattern is seen with the left hand. Curve fits are based on a mixed-effects linear model regressing the amount of joint movement onto age and hand.

Figure 5.

The average percentage of total angular change accounted for by the shoulder, elbow and is shown when using the left hand (a) and the right hand (b). Significant Age x Hand interactions for all three joints show that with increasing age children show more distally controlled movement with their right hand: decreased contribution by the shoulder and elbow while the wrist contribution increases. This pattern was not evident with the left hand. Curve fits are based on a mixed-effects linear model regressing the percentage which each joint contributed to the overall movement onto age and hand.

Figure 6.

The probability of successfully striking the peg as a function of the overall amount of angular change of the elbow and wrist are shown (a). Children are more successful with increasing use of the wrist, while increasing use of the elbow is predictive of less accuracy. Children also were more accurate at striking the peg when moving the hammer smaller distances during a strike (b). Curve fits are based on binomial GEE models using a logit link function and regressing the probability of accurately striking the peg onto elbow and wrist movement as well as the overall distance travelled by the hammerhead.

Figure 7.

The probability of hitting the peg successfully depending on the outcome of the prior strike is shown (a). A significant effect shows a higher success rate following hits than misses. Adjustments to the outcome of the prior strike were found in the hammer velocity (b). Children significantly increased the hammer velocity after hits and decreased hammer velocity following misses.