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Ontogeny of tool use: how do toddlers use hammers?

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Abstract

Hammering with a hand tool appears early in life. Skillful hammering involves accommodating movements to properties of the hammer, orienting the hammer's head to the item to be struck, and maintaining stable posture during forceful action with the arm(s). We aimed to characterize development of these abilities in young children (12, 18, and 24 months old). Children struck at a peg with a hammer held in the hand or a hammer attached to a handle. Children struck more frequently with a hard hammer surface than a soft one, and more frequently (although less accurately) with handled hammers than with non-handled hammers. Developmental differences were evident in accuracy, number of strikes, and kinematic parameters, especially with the handled object. Children's ability to use objects for forceful and accurate percussion changed measurably over the second year, in tandem with improving postural stability and greater motion of the elbow.

KEYWORDS
ecological psychology, hammering, kinematics, manual coordination, percussion

1 | INTRODUCTION

Tool use by young children affords a means of studying skill development and problem-solving (e.g., Chen & Siegler, 2000). Hammering, or using an object to strike a surface, is an early-appearing form of percussive tool use during a child's development. Our understanding of the motor development of percussive tool use, particularly for very young children, is expanding (Biryukova & Bril, 2012; Fitzpatrick, Wagman, & Schmidt, 2012; Kahrs, Jung, & Lockman, 2014; Lockman, 2008). Striking an object against a surface in an exploratory/play context appears roughly by about five to six months of age (Gibson & Pick, 2000; Kahrs, Jung, & Lockman, 2013; Lockman, 2000). Actions like this, that infants produce by the end of the first year of life, contribute to the emergence of percussive tool use (hammering) in the second year of life (Kahrs, Jung, & Lockman, 2012, 2013). Skill at hammering develops gradually from then on, and with extensive practice can become extremely refined, as described for example by Bril, Roux, and Dietrich (2005) for artisans hand-crafting beads.

Analyzing how children move their bodies and use hammers is one way to understand the ontogenetic origins of skilled tool use from an ecological psychology perspective (Bril, Rein, Nonaka, Wenban-Smith, & Dietrich, 2010; Kahrs et al., 2013, 2014; Osiurak, Jarry, & Le Gall, 2010). We investigated the movements, sensitivity to the properties of a percussive tool, and posture of young children between 1 and 2 years of age, a period of rapid development in children's manual proficiency (e.g., Connolly & Dlagleish, 1989) as they hammered a peg into a pegboard.

Understanding the development of percussive striking in children may also provide insight into the origins of this form of tool use in our hominin ancestors. Hammering with a hand tool is the earliest known form of tool use in human history, used to process tough foods (e.g., nuts), and to knap stones to make other tools (Goren-Inbar, Sharon, Melamed, & Kislev, 2002; Roux & Bril, 2005). Among nonhuman primates, chimpanzees, capuchin monkeys, and long-tailed macaques also use hammer tools to prepare tough foods for consumption (Boesch & Boesch-Achermann, 2000; Fragaszy, Izar, Visalberghi, Ottoni, & Gomes De Oliveira, 2004; Gumert, Kluck, & Malaivijitnond, 2009; Kortlandt, 1986; Matsuzawa, 2001). Only a few non-primate species have demonstrated this behavior (e.g., otters, Hall & Schaller, 1964), suggesting a primate specialization for percussive action. The adjustments in action and posture that accompany the development of hammering in young children may illustrate some of the challenges that percussion poses to primates.

From an ecological perspective, goal-directed movements, such as hammering, are self-organized through the dynamic interactions of the body, the environment, and the demands of the task (Bernstein, 1967, 1996; Bril et al., 2010; Fitzpatrick, Aguilar, Garry, & Bongers, 2013; Gibson & Pick, 2000, Newell, 1986; Savelsbergh, van der Kamp, & Rosengren, 2006; Thelen & Smith, 1994). For a typical manual hammering task in modern western society, and the task provided to the children in the current study, the performer's goal is to use the tool to drive the object into the substrate (e.g., use a hammer to drive a nail into a piece of wood) using minimal effort. Therefore, the mechanical sub-goals likely include using minimal energy expenditure (Fitzpatrick et al., 2012; Neilson & Neilson, 2005) while striking with a high degree of accuracy. High accuracy is related to accomplishing the goal (Biryukova, Bril, Frolov, & Koulikov, 2015) while minimizing unnecessary energy expenditure (Fitzpatrick et al., 2012; Neilson & Neilson, 2005) and reducing risk of injury.

We anticipated that older compared to younger children would be more accurate in striking a peg using a hammer, in part because their arm movements would display greater self-organization toward movement patterns that could improve accuracy. Experts hammering nails utilize upper extremity joint motions that occur primarily in the sagittal plane, minimizing left-right movement variation that might increase striking error (Côté, Raymond, Mathieu, Feldman, & Levin, 2005). Therefore, we expected that older children would produce arm motions closer to this pattern than younger children, whom we expected to engage in movements that could increase side-to-side hammer striking errors.

Coordination of multiple joints for an action also influences energy expenditure. Currently, the age-related emergence of arm movement coordination within a hammering context is unclear. Kahrs et al. (2014) observed that increasing age was associated with increased wrist movement and decreased shoulder and elbow movement in children 19–36 months old in a hammering task similar to ours. However, this pattern occurred only when the children used their preferred hand. Apart from Kahrs et al. (2014), most of our understanding of the development of multi-joint arm movements of young children is based on tasks with different goals and demands, such as reaching (e.g., Traynor, Galea, & Pierrynowski, 2012) and using a spoon (e.g., Connolly & Dlagleish, 1989), or involve children younger or older than those of this study (1–2 years).

Related to energy considerations, we anticipated that the older, compared to younger, children would produce greater downward hammer velocity (greater kinetic energy). Our rationale is that for a given percussive task, based on the physical principle of the work-energy theorem and the assumption of self-organization of movements, it is likely that there are optimal combinations of muscular force magnitudes, hammer displacements, and number of strikes. There is an energy cost tradeoff between the mechanical energy produced by muscle mechanical work (muscle force applied to hammer × hammer displacement) for each strike, and the number of strikes needed to accomplish the task. Expert stone knappers, for example, consistently generate only the amount of mechanical energy needed, in contrast to inconsistent and greater amounts produced by less-skilled knappers (Bril et al., 2010).

Older, compared to younger, children were also expected to produce greater hammer displacement through greater rotation about all of the upper limb. As children between 1 and 2 years of age are in early stages of developing multi-joint arm coordination (Traynor et al., 2012), we expected that younger children would move their arms primarily about a single joint, specifically the shoulder joint, the most proximal joint (Kahrs et al., 2014; Konczak & Dichgans, 1997; Traynor et al., 2012). According to Dounskaia (2005), when learning a new motor skill, an individual must learn to regulate and exploit additional dynamics about distal joints (wrist and elbow, in the case of hammering) to maximize “efficiency” of effort. Consequently, we expected that older children would exhibit increased magnitudes and variability in elbow and wrist joint motion compared to the younger children (Biryukova et al., 2015; Savelsbergh et al., 2006).

Within an ecological perspective, a person's understanding of the affordances of a situation, in part by coupling salient perceptual information to one's actions, is crucial for developing appropriate motor control and coordination for effective tool use. Affordances (Gibson, 1977, 1979) are the relations between the individual organism and the features of the environment that provide all possible actions with an object to accomplish any given task (Chemero, 2003; Reed, 1996). Understanding of affordances for percussive tool use first emerges from children's exploratory action routines of manipulating objects with the hand(s) (Connolly & Dlagleish, 1989; Kahrs et al., 2013; Lockman, 2000) and striking various surfaces using their hands and held objects. Before their first birthday, children begin to bang hard objects more often than soft objects against a hard surface (Bourgeois, Khawar, Neal, & Lockman, 2005; Fontenelle, Kahrs, Neal, Newton, & Lockman, 2007). These actions indicate that infants are learning to couple perceptual information to their arm movements (Connolly & Dlagleish, 1989; Gibson & Pick, 2000; Savelsbergh et al., 2006).

Coupling perceptions with percussive arm actions continues to develop during early childhood. Bourgeois et al. (2005) observed that children younger than 1 year modulate their percussive behavior when striking a hand-held object against a surface. Fitzpatrick et al. (2012) observed children 3–5 years old hammering pegs into a pegboard using hammers with differing linear and rotational inertial properties. The children discriminated some of the hammer's inertial properties, as they modulated some features of performance with the different hammers, but other features of performance (e.g., hammer displacement) were unaffected.

We extend the ecological research on children's hammering by investigating how 1–2 year-old children explored and used hammers in response to two varying hammer properties: the hardness of the hammer's striking surface (foam, wood) and presence or absence of a handle. To test our predictions, hammers with different combinations of hardness and handle type were presented to the children. We predicted that children would strike more frequently when they struck with a rigid surface rather than a compliant surface, and with a handled hammer than a non-handled hammer. We surmised the latter would occur because the children would exploit affordances that are different for the handled compared to non-handled hammer: mechanical properties (e.g., increased kinetic energy of the hammer head) that increase the potential for greater striking velocity independent of increasing segmental velocities (Wagman & Carello, 2001). To exploit these mechanical properties, children striking while holding a hammer near the end of the handle should displace the hammer farther and move the hammer head with greater velocity than when they strike with a non-handled hammer. Finally, the handle alters the spatial relation between movement of the hand and movement of the hammer's striking surface, resulting in a more complex object manipulation than that required for a handle-less hammer. The combination of greater velocity and greater momentum when using a handled hammer should make controlling the strike more difficult than when using a non-handled hammer. Thus, we predicted that striking movements would be less accurate when young children struck with the handled than the non-handled hammer.

We anticipated that older, compared to younger, children would capitalize on different affordances. Twelve to eighteen month-old children exhibit some anticipatory positioning of the hand prior to grasping an object in a manner appropriate for its familiar use (e.g., Barrett, Davis, & Needham, 2007). At 18 months old, children orient their hand correctly to insert it into a slot, but not until 24 months do children orient a disk to insert it into a slot (Street, James, Jones, & Smith, 2011). Thus, we expected to find that older children more often than younger children would orient the hard surface of the hammer to strike the peg and would more often re-orient the hammer between strikes after striking with the soft surface of the hammer, when using a hammer with both hard and soft surfaces.

In sum, we predicted that older children compared to younger children would strike more accurately and with greater downward velocity, and would exhibit greater motion of the elbow and wrist joints while striking. We predicted that the children would strike more often with the rigid side of the hammer head toward the peg when given a hammer with rigid and compliant surfaces, and we expected that older children would do so more reliably than younger children. Finally, we predicted that children would achieve greater displacement of the hammer and strike with greater velocity when using a hammer with a handle than one lacking a handle, although we expected that they would be less accurate when striking with a handled hammer.

Although our primary research interests focused on the children's arm movements exhibited while hammering, we recognize that limb activity occurs within the body's postural context. Postural adjustments contribute to preparation as well as execution of arm movements (e.g., Ledebt & Savelsbergh, 2014) and postural control is necessary for accurate performance of voluntary movements (van der Fits & Hadders-Algra, 1998) but postural strategies are still developing during early childhood (Viholainen, Ahhonen, Cantell, Tolvanen, & Lyytinen, 2006). For seated reaching (a more stable task environment than ours), postural adjustments are not necessarily displayed by children up to 18 months of age (van der Fits & Hadders-Algra, 1998). We have little information on the postures used by children between 1 and 2 years of age, particularly for performing a percussive task placed on the ground without external postural support (such as a chair back). We qualitatively assessed the stability provided by the different sitting positions displayed by the children. This qualitative analysis is a first step toward understanding dynamic interactions of posture and limb activity in children of this age.

2 | METHOD

We used a 2 × 2 × 3 (HANDLE × HARDNESS × AGE) experimental design to evaluate kinematics and behaviors displayed during striking with hammers of varying properties by young children of differing ages. For the hammer, the factor HANDLE included “no handle” (NO HANDLE) and “with handle” (HANDLE) conditions. The factor HARDNESS refers to the composition of the hammer head, that is, a cube made of foam and wood (F/W) or wood only (W). Each child was given the opportunity to perform the task using each of the four hammer combinations.

2.1 | Participants

We recruited from the local community 27 children (ages: 12, 18, and 24 months; ±2 weeks of birth date) with no known health, mental, or physical impairments. Two children (both 12 months old) chose not to attempt any of the test tasks and were dropped from the study. The final sample included seven 12-month olds (4 boys, 3 girls), nine 18-month olds (7 boys, 2 girls), and nine 24-month olds (6 boys, 3 girls).

2.2 | Materials and equipment

After the child attained a sitting position on the floor in front of the parent, a panel (composed of PVC) with holes in the top surface (hereafter, the “pegboard”) was placed directly in front of and at midline of the child within the child's arm reach (Figure 1). The task was to use a hammer to hit (or attempt to hit) the top of a cylindrical peg (PVC; 2.5 cm diam × 7.0 cm long) that had been placed partially into a matching hole in the pegboard (30 × 15 × 6 cm^3 high) until the peg would not move any further or dropped through the pegboard onto the floor (Figure 2). Each of the four hammers had a 3.0 cm^3 cube head that was either solid wood or an equal combination of foam and wood. For the F/W HANDLE tool, the panels of foam and wood were aligned so that the handle was sandwiched between one face of each material (Figure 3). The handle, when present, was a wood dowel 13.0 cm long × 0.6 cm diameter, covered with thin (0.1 cm) black felt. The masses were as follows: W cube = 24 g, the F/W cube = 13 g, and the handle = 7 g. All features of the hammers were flat black except for a reflective marker centered on each flat surface the hammer head. Although adults could visually distinguish the F/W cubes from the

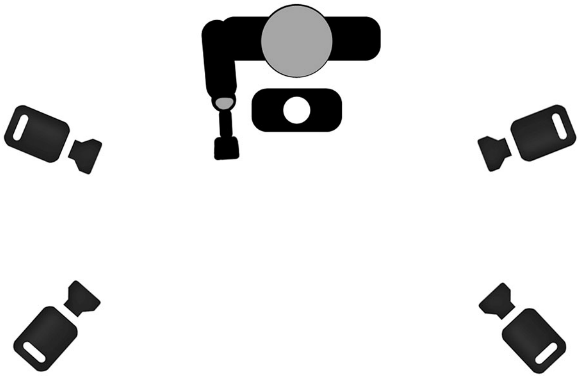

FIGURE 1 Experimental setup. Not to scale

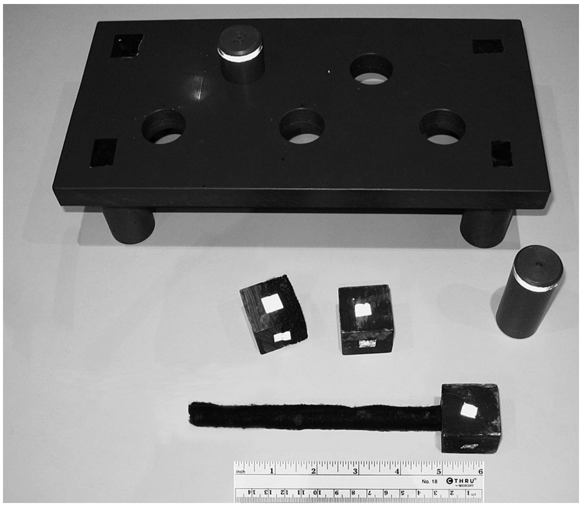

FIGURE 2 Photo of pegboard with pegs and handled and non-handled hammers

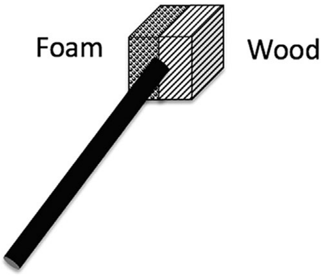

FIGURE 3 Sketch of the hammer composed of foam and wood, with the handle attached at the interface of these two materials. A hammer of the same composition, but without a handle (not shown), was also presented

W cubes, and the foam surface from the wood surface of the combination cubes, they were relatively similar in appearance.

For motion measurement, as shown in Figure 1, three genlocked-video S-VHS cameras and one prosumer, 3-CCD camera (60 fields/s) were used to capture the spatial locations of reflective markers within an approximately 1.00 m^3 calibrated volume. A 3-dimensional calibration device was recorded by all cameras prior to the start of testing on each test day. Reflective markers (spheres or strips of reflective tape) were placed on the flat surfaces of the hammer, the corners of the pegboard, the perimeter of the superior edge of the peg, and on the child's skin or a form-fitting, specially sewn long-sleeved black shirt worn by the child. The participant markers were placed on both upper extremities at the shoulder and elbow joints, midpoint of the dorsal surface of the wrist joint, and distal head of the 2nd metacarpal, as shown in Figure 4. The four cameras were sufficient to capture the markers' locations in 3-dimensions.

2.3 | Procedure

We instructed the parent to allow the child to work at the task in his or her own way, without parental assistance except to model the appropriate action when asked to do so by the investigator. The experimental session began when the child attained a stable seated position on the floor in front of the parent. Once the child was positioned, the experimenter, who sat near the child and guardian, placed the pegboard and peg in front of the child's midline, modeled the task, then offered the child the hammer. Once handed the tool, the child was permitted to reposition his/her body if desired, and to act freely with the hammer and peg, or to use the hands to manipulate the peg directly. If the child did not show interest in the task, the task was again modeled for the child by the guardian and/or the investigator.

If the child's behavior approximated the task, he or she was allowed to continue until the task was accomplished or the child stopped making striking motions. This was considered one bout. The peg panel then was reset, and the child was given the opportunity to repeat the task with the same tool until five bouts had been performed or the child displayed no further interest in the task, whichever occurred first. Prior to starting the next hammer condition, the child was given the opportunity to perform one of three bimanual manipulation tasks (drumming wooden sticks on a plastic drum, sliding two objects along bilaterally symmetric grooved tracks, and clapping wooden cymbals). Data from these conditions were analyzed separately and are reported in Brakke, Fragaszy, Simpson, Hoy, & Cummins-Sebree (2007). The order in which the hammer and bimanual task conditions were presented was counterbalanced within age groups.

2.4 | Data reduction and analysis

2.4.1 | Behavior

We used three scoring protocols for behaviors related to the use of the hands and striking outcomes: Posture, Hand Actions, and Arm Movement Strategy (the qualitative assessment of the movements

Marker	Location
Shoulder	Tip of the acromion process
Elbow	Lateral humeral epicondyle
Wrist	Midpoint of the dorsal surface of the radio-carpal joint space
Hand	Distal head of the 2nd metacarpal

FIGURE 4 Location of markers on participants, and definitions of their locations

used to bring the arm-hand-hammer downwards to contact the peg/pegboard). These are explained below.

2.4.2 | Posture

To illustrate the variety of various body postures used per age group and hammer condition, we used a qualitative methodology best defined as “template analysis” (King, 1998, 2004). Following review of the video corpus, we created an ethogram of 16 body positions exhibited during hammering (Figure 5). We used this ethogram to code each child's posture displayed during each bout of striking. Children did not change postures within bouts of striking. We grouped individual postures into two major posture types (“sitting,” a sitting position with most of weight on pelves; and “nonsitting,” a position with weight on legs and feet) and two sublevels specifying symmetrical or asymmetrical position of the legs. From these data, we generated frequency counts per child per hammer condition of each of the major posture types and sublevels. Two observers trained in this coding under the supervision of KS.

2.4.3 | Hand actions

Any motion by the hand toward the peg, whether the hand or hammer made contact with the peg or pegboard, or if the child missed both, was counted as a *hand action*. We scored all hand actions that we could see sufficiently from video playback using the following categorical scheme: a) surface contacted (peg or pegboard); b) form of action (push or strike); and c) striking object (hand or hammer) that made contact with the surface, when contact was achieved. If the child struck the peg, we noted an accurate strike. For form of action, a push was scored if the child maintained pressure against the peg after making contact; a strike was a rapid motion with brief contact and quick release of pressure on peg or substrate. In the F/W conditions, the surface of the cube (W, F, or F/W) that made contact with the peg or pegboard was recorded when it was not obscured by the child's hand. Subsequently, hand actions where no contact was made with peg or pegboard were discarded. Observers practiced the coding method until the percentage of agreement for each behavior with S C-S over two consecutive training coding episodes reached ≥85%.

The following hand action variables were generated: total attempts and accuracy, form of hand action, and surface of the striking object that made contact with peg or pegboard. For each participant within each hammer condition, we expressed the form of hand action as a proportion of the total attempts, and for strikes (excluding “pushes”), the surface contacted and accuracy (number of times peg was struck) as the proportion of the total strikes. These data were analyzed using general linear models, with age as a continuous factor. A Poisson distribution was used unless the model did not converge with this distribution. In those cases, a negative binomial distribution was used. We report estimates (EST), standard error (SE) of the estimates, and two-tailed probabilities. Estimates for Age are given in units per month. The relation between accuracy and other behavioral and kinematic parameters was assessed using Pearson correlations. Spearman correlations were used to assess the relation between placing the foam side of the hammer against the peg and pushing or striking.

2.4.4 | Kinematics

For kinematic analyses, we analyzed all bouts that contained three or more striking attempts using the cube. Each strike cycle was digitized

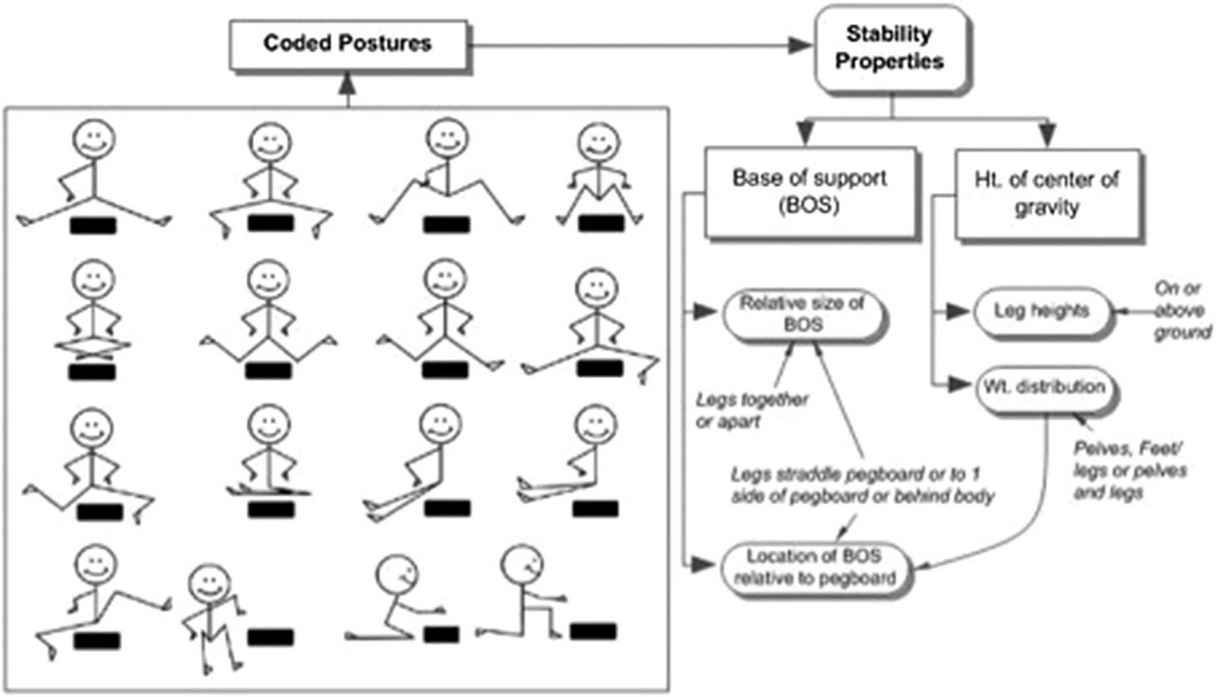

FIGURE 5 The childrens’ postures and their stability properties. All childrens’ performances were coded into the 16 postures shown. Stability properties of postures were derived by classifying the locations of the legs and the surfaces of the child that supported body weight as shown by italicized descriptors

for these bouts, using the Peak Motus Measurement System™ (v.4.2, Vicon, Inc.; Oxford, UK). A strike cycle was defined as the time from the maximum height of the hammer head until the hammer head again achieved maximum height. Within each cycle, the kinematics of the down phase (the time from the maximum height of the hammer head until the hammer achieved its lowest vertical position) were analyzed. Following data filtering (optimally-regularized Fourier series; Hatze, 1981), linear displacement of the center of the hammer head was standardized to arm length (% ARM-L). Angular displacements of the resultant elbow and wrist angles, the upper arm angle relative to vertical angle, and total arm displacement (sum of these upper extremity displacements) were generated. Maximum angular velocities of the upper extremity angles were derived.

Eighteen participants (four 12-month olds, six 18-month olds, and eight 24-month olds) contributed kinematic data. Kinematic variables for the remaining subjects could not be coded because their bouts contained fewer than three strikes. Generalized linear models using age as a continuous variable were used, using Poisson or negative binomial distributions to normalize the distribution of the data. Few kinematic bouts existed for striking with the F/W side of the hammers and preliminary statistical analyses indicated that kinematic differences between the two conditions of HARDNESS (W and F/W) within each age group were non-significant. Therefore, the data were collapsed across HARDNESS conditions for subsequent analyses. To provide a qualitative representation of kinematic movement organization, absolute phase-plane portraits of the upper extremity angular kinematics were graphed.

3 | RESULTS

Our behavioral data set was composed of 2,703 hand actions with contact with a surface, including 2,390 contacts on the peg or pegboard with the hammer and 313 contacts on the peg or pegboard with the hand directly. A summary by age group of the behavioral data set is provided in Table 1.

3.1 | Posture

The number of different postures exhibited did not vary across age groups. As shown in the classification tree of Figure 5, 14 (87.5%) of the 16 observed postures were classified as sitting postures (most of body weight supported by pelves), and of those, 10 postures were symmetrical. The symmetrical sitting postures comprise: a) four different “straddle” sits, in which both legs straddled the pegboard; b) four “legs together;” and c) two “other.” The nonsymmetrical sitting postures involved having one leg lying on the ground while straddling the pegboard, with the knee flexed or extended, and the opposite leg positioned elsewhere in a different configuration. Only two of the 16 postures were non-sitting postures, in which weight was supported by the legs or feet: “1-leg kneeling” and “2-leg kneeling” (kneeling onto both legs while sitting back onto the legs).

Thus, a sitting position was the most common position displayed, and all children of all age groups used a sitting position during at least one bout. Non-sitting positions were assumed by only three children (one 12 months, two 18 months) who each used them during 1/3 of their bouts. Among the symmetrical sitting positions, the straddle position was used by 88% of the 12-month olds, 78% of 18-month olds, and 67% of 24-month olds. Asymmetrical leg positions, in which one or both legs did not rest on the floor, but were supported instead by one or both feet, were used by about two-thirds of 12- and 24-month-old children and about one-third of 18-month olds.

3.2 | Actions

The GLM using Age, Handle Condition, and Hardness as predictors indicated a significant effect of Age on the frequency of bouts (EST = 1.23, SE = 0.02; $p = 0.0003$). Older children produced more bouts of striking than younger children (mean per condition, ±SD: 12 months = 4.1 ± 2.9; 18 month *s* = 4.8 ± 2.9; 24 months = 8.7 ± 2.9). Material and Hardness did not significantly predict the frequency of bouts.

Across all conditions, all children except two 18-month olds used the hammer proportionally more often than their hand to contact the peg. The two children that used the hand more often than the hammer typically produced a single action per bout, touching the peg once with the hand. We focus the remainder of our analyses on actions using the hammer (thus, excluding actions with the hand alone).

3.2.1 | Using the hammer: effects of handle and hardness on striking

Children typically gripped the handled hammer at the distal end of the handle, as would an adult, rather than at the point where the handle joined the cube. This aspect of behavior did not vary across Hardness conditions. Children made proportionally more strikes per bout with a handled hammer than with a non-handled hammer (EST = 1.76, SE = 0.11 $p < 0.0001$, Handle) (Table 1). Hardness was also a significant predictor for this variable: children made proportionally more strikes per bout with the wood hammer than the wood/foam hammer (EST = 1.12; SE = 0.04, $p = 0.0074$). Age was not a significant predictor for this variable.

Children made more total strikes with the handled hammer than with the non-handled hammer (EST = 1.81, SE = 0.173, $p = 0.001$). For this variable Age was a significant predictor as well (EST = 1.106, SE = 0.032, $p < 0.006$), but Hardness was not. Older children produced more strikes than younger children.

Childrens' actions with the combination wood/foam hammer varied in ways that suggested that they were responsive to the material properties of the hammer head. The cube with the handle had five sides that could make contact with the peg: one all wood, one all foam, and three containing foam and wood contact surfaces. The cube without the handle had six sides, and thus an additional foam-wood side. Thus, depending on the presence of a handle, the expected distribution of striking on the various sides of the cube is 0.17–0.20 for the wood side, 0.17–0.20 for the foam side, and 0.60–0.67 for the combination side.

Children struck at the peg with the wood sides of the combination F/W hammer (41% of strikes) approximately twice as often as

TABLE 1 Individual mean number of bouts and number of actions[a], and proportion[b] of the three most common forms of action

Age group	Handle	Material	Mean bouts, SD	Mean actions per bout, SD	Mean total actions	Mean proportion hand directly toward peg	Mean proportion push peg with hammer	Mean proportion strike toward peg with hammer
12 months	No	Wood	4.57,	2.34,	10.69	0.12	0.15	0.44
($N = 7$)			4.86	2.67				
	No	Wood + Foam	2.29,	2.99,	6.85	0.2	0.14	0.66
			1.60	1.59				
	Yes	Wood	4.71,	3.87,	18.23	0.19	0	0.57
			3.64	2.88				
	Yes	Wood + Foam	4.71,	3.47,	16.34	0.19	0	0.64
			5.41	2.21				
Mean per condition			4.1	3.17	13.02	0.17	0.07	0.58
18 months	No	Wood	4.56,	2.11,	9.62	0.3	0.37	0.33
($N = 9$)			3.21	1.17				
	No	Wood + Foam	4.44,	3.01,	13.36	0.34	0.1	0.44
			3.75	2.91				
	Yes	Wood	5.11,	4.97,	25.4	0.17	0.05	0.75
			4.08	2.34				
	Yes	Wood + Foam	5.00,	4.28,	21.4	0.22	0.04	0.56
			3.87	6.57				
Mean per condition			4.78	3.59	17.44	0.26	0.14	0.52
24 months	No	Wood	7.44,	4.02,	29.91	0.29	0.18	0.53
($N = 9$)			4.19	2.42				
	No	Wood + Foam	9.67,	2.97,	28.72	0.2	0.3	0.5
			3.39	1.34				
	Yes	Wood	9.78,	7.96,	77.85	0.08	0.15	0.74
			7.68	5.10				
	Yes	Wood + Foam	7.78,	6.35,	49.4	0.17	0.16	0.64
			6.40	4.70				
Mean per condition			8.67	5.33	46.47	0.18	0.2	0.6

[a] Any motion by the hand toward the peg, whether or not the hand or hammer made contact with the peg or pegboard.
[b] Proportions do not add to 1.000 because other varieties of actions also occurred.

expected (proportion of all strikes = 0.41, vs. 0.17–0.20, expected), and more often with the wood side than with the foam side ($t\ (16) = 3.75$, $p = 0.002$). The foam side of the F/W hammer was used to strike at the peg in just 13% of strikes, and the foam/wood combination side accounted for 32% (the remaining 14% of strikes were not classified because they were ambiguous). The Handle condition strongly predicted the proportion of strikes using the foam side of the hammer when only the foam and wood sides were tallied (so that they had equal likelihood of use) (EST = 4.33, SE = −0.64, $p = 0.028$. Another indication that the children were responsive to the material properties of the hammer is that the more often children placed the foam side of the hammer against the peg, the more likely they were to push ($r_s = +0.49$, $N = 17$, $p < 0.05$) and the less likely they were to strike ($r_s = -0.58$, $N = 17$, $p = 0.001$.

We coded which surface of the cube struck the surface first in one or more bouts of striking with the Handled F/W hammer for the 17 children for whom we could code this variable. The children used the wood side of the hammer in a great majority of the coded first strikes (53 of 61). The children used the wood or foam surface first in 61 bouts. (Other children used the combination wood/foam side for first strikes, did not strike in these conditions, or we could not determine which side was used in the first strike of the bout; total 49 bouts.) Fifteen of the 17 children made the first strike in a bout more often with the wood side than the foam side (χ^2 (1 df) = 8.41, $p < 0.05$). Use of the foam or wood side of the hammer was more evenly distributed in the No Handle condition: 28 first strikes with the wood side, 24 first strikes with the foam side, one first strike with a wood/foam side (distributed across 13 children), and 45 bouts for which we could not determine which side struck first.

We examined how children oriented the hammer in the F/W Handle condition. Children looked at the peg while striking, not at the head of the hammer. Occasionally children looked at and touched the head of the hammer when given a handled hammer with a F/W cube, before they struck with it. During this exploration, they sometimes felt the cube, pressing a thumb against the foam side, but they did not alter the orientation of the hammer after these actions and before striking with it, nor did they rotate the handle of the hammer between strikes, which would reorient the side of the cube that would strike the peg on the next strike, even when they passed the hammer from one hand to another. Often they hit the peg with an edge of the cube, rather than a flat side. When they did so, the force of the strike turned the wood side of the cube towards the peg.

3.3 | Accuracy

Age was a significant predictor of the proportion of strikes which hit the peg (EST = 1.16; SE = 0.02, $p < 0.001$). Our youngest age group struck the peg with the hammer on about one quarter of strikes ($M = 0.28$, SD = 0.23); the 18-month olds on two-thirds of strikes ($M = 0.66$, SD = 0.32); and the 24-month olds on seven-eighths of strikes ($M = 0.86$, SD = 0.10, respectively) (Figure 6). Post hoc comparisons using the Tukey's *t*-test indicated that a smaller proportion of accurate strikes were made by 12-month olds than 18- and 24-month olds ($p < 0.001$, both cases) and 18- and 24-month-old children did not differ from each other. A GLM model using Handle and Hardness as predictors indicated that Handle was a significant predictor (EST = −0.17, SE = 0.07, $p = 0.02$) but Hardness was not and the interaction of Handle and Hardness was not significant. Children were less accurate with the Handled hammer than the Non-handled hammer (Figure 6).

We found very modest correlations (none with $p < 0.05$) between accuracy and other aspects of performance: mean number of strikes per bout (r_{xy} (25) = +0.28); total number of strikes (r_{xy} (25) = +0.19), percent of hits with wood side in F/W conditions (r_{xy} (19) +0.11, F/W non-handled hammer, and r_{xy} (20) = −0.22, F/W handled hammer), and for handled conditions, Max downward velocity (r_{xy} (18) = +0.31), Mean elbow displacement, (r_{xy} (18) = +0.41), and Mean wrist displacement (r_{xy} (18) = +0.12).

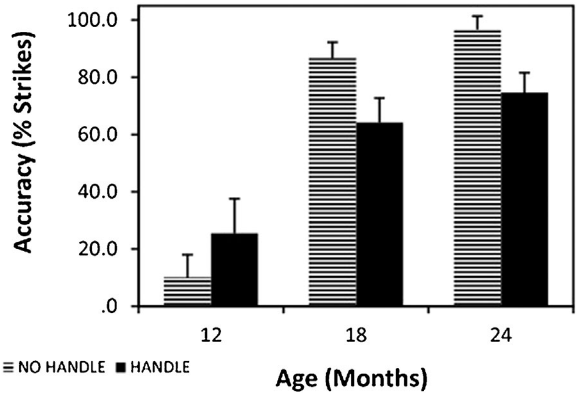

FIGURE 6 Percentage of strikes with the hammer that contacted the peg (accurate strikes) as a function of age and of the presence or absence of a handle on the hammer. Error bars represent standard error of the mean

3.3.1 | Kinematics

Hammer kinematics

Cycle frequency was consistent between handle type and across ages, ranging from 2.2 to 4.0 Hz for individual participants (no comparisons significantly different). GLM's for kinematic variables used Age and Handle as separate predictors. We examined displacement of the hammer when scaled to arm length (% ARM-L) (i.e., normalized). Normalized displacement of the hammer did not distribute normally, even after transformation, so no GLM could be run. Accordingly, we report descriptive statistics only. The hammer head moved farther when it was attached to a handle, and greater gains in displacements were displayed with age for the HANDLE condition. The 12-month olds displayed displacements less than half of their arm length (Median + IQR: 41% + 12, HANDLE, and 41% + 6, NO HANDLE). The 24-month olds, in contrast, tended to increase their displacements during HANDLE (Med = 86% + 25) compared to the NO HANDLE conditions (51% + 30). That is, 24-month-olds moved the end of the hammer substantively farther when it had a handle than when it did not, well beyond the displacement afforded by the handle itself (a few centimeter).

The Handle condition significantly predicted maximum downward velocity of the hammer: the children moved the handled hammer faster than the non-handled hammer (EST = −0.56, SE = 0.10, $t = 5.42$, df = 8, $p < 0.0006$. Age was not a significant predictor for this variable ($t = 1.69$, df = 9, $p < 0.12$). Values (MED + IQR) for maximum downward linear velocity ranged from $0.82 + 0.56\,\mathrm{m \cdot s^{-1}}$ (12 months) to $1.79 + 0.71\,\mathrm{m \cdot s^{-1}}$ (24 months) during HANDLE cycles, and from $0.63 + 0.05\,\mathrm{m \cdot s^{-1}}$ (12 months) to $0.93 + 0.31\,\mathrm{m \cdot s^{-1}}$ (24 months) during NO HANDLE cycles. Thus, maximum velocities were approximately 50% greater for the HANDLE compared to NO HANDLE conditions for 12-month olds, and 100% greater for 24-month olds, with 18-month olds displaying intermediate values.

Angular kinematics

Angular displacements are summarized in Table 2. Age significantly predicted angular displacement of the elbow (EST = ln 0.73, SE = 0.03, $t = 2.79$, df = 9, $p = 0.021$) but not the wrist. Handle condition did not significantly predict elbow or wrist displacement. The oldest age group displayed approximately twice the elbow displacement as the other age groups, due to these children tending to start elbow joint extension from a more flexed position. Median elbow displacements were 22° + 1° and 29° + 5°, NO HANDLE and HANDLE conditions, respectively, for 24-month olds, vs. 9–10 + 1–3 and 8–12 + 0–3 NO HANDLE and HANDLE conditions, respectively, for the other two age groups. Wrist displacement varied by only a few degrees among the three age groups (Medians 13° to 15°).

Maximum elbow extension velocity was not significantly predicted by Handle condition, but was significantly predicted by Age (EST = 0.63, SE = 0.20, df = 9, $p < 0.011$). Median values for maximum elbow extension velocity were, for NO HANDLE trials, $309\,\mathrm{m \cdot s^{-1}} + 85$ for 24 months; $121\,\mathrm{m \cdot s^{-1}} + 18$ for 18 months; $121\,\mathrm{m \cdot s^{-1}} + 47$ for 12 months ($H = 6.000$, $p = 0.05$) and for HANDLE trials, $354\,\mathrm{m \cdot s^{-1}} +$ 99 for 24 months, $96\,\mathrm{m \cdot s^{-1}} + 104$ for 18 months; $90\,\mathrm{m \cdot s^{-1}} + 43$ for

TABLE 2 Medians and interquartile ranges (IQR) of angular displacements (degrees) and velocities ($m \cdot s^{-1}$) for NO HANDLE and HANDLE conditions

		Age group (months)					
		12		18		24	
		No Han[a]	Han[b]	No Han	Han	No Han	Han
Variable	**N:**	**3**	**4**	**2**	**6**	**5**	**6**
Ang. displacement							
Upper Arm	Median	10.2	16.8	13.5	7.0	15.4	15.8
	IQR	7.3	5.3	2.1	4.8	4.4	7
Elbow	Median	11.9	10.1	9.3	9.9	22.4	28.6
	IQR	3.5	4	1.1	11.6	11.6	5
Wrist	Median	15.1	10.3	13	14.8	14.3	23
	IQR	6.4	5.4	4.4	25.2	2.6	15
Total Arm	Median	33.8	35.6	36.5	26.8	50.4	71.1
	IQR	15.5	10.8	6.2	23.1	17.3	23.3
Ang. velocity							
Upper Arm	Median	66.4	124.1	152.9	80.6	97	164.6
	IQR	78.6	69.5	9.8	84.7	48.7	53.4
Elbow	Median	121.4	90.2	121	96.3	309.4	353.5
	IQR	56.7	42.4	17.1	103.3	85.8	98.7
Wrist	Median	113.5	148.7	247.1	160.8	147.7	132.1
	IQR	217.3	65.8	51.9	170.6	128	19.4

[a] No Handle.

[b] Handle.

12 months ($H = 8.095$, $p = 0.017$). Wilcoxon Mann–Whitney tests revealed that maximum elbow extension velocity was significantly faster for the 24-month-old group than for the two younger age groups combined in the NO HANDLE condition ($w_x = 12$, $m = 4$, $n = 5$; $p = 0.032$, and the contrast approached significance in the HANDLE condition ($w_x = 13$, $m = 4$, $n = 5$; $p = 0.056$) .

To provide a qualitative representation of kinematic movement organization, absolute phase-plane portraits (velocity-angle graphs) for one representative child from each age group for one bout of NO HANDLE and HANDLE conditions are shown in Figures 7 and 8. Visual inspection revealed that, consistent with the group kinematic HANDLE results described earlier, the 12- and 18-month old children tended to move the joints through lower amplitudes and lower velocities than the 24-month old. The qualitative change from high consistency across cycles of the phase-plane portraits of the youngest child to the greatest inter-cycle variations demonstrated by the 24-month old is interesting. Some of the observed inter-cycle variation of the 24-month old appears to be a shift in start/end angles across cycles rather than a change in the angular displacement; other variation was due to the tendency of the displacements and velocities to decrease over time within the bout.

4 | DISCUSSION

We examined a set of related predictions concerning hammering by children between 12 and 24 months of age, when coordination of arm movements and of postural control are developing substantively (Adolph & Berger, 2007) and when goal-directed hammering is emerging (Kahrs et al., 2014). Our study complements recent studies on hammering in toddlers (Fitzpatrick et al., 2013; Kahrs et al., 2012, 2013, 2014) with respect to the age range of the children, the different types of hammers presented, attention to posture, and additional information about arm kinematics.

Skilled hammering requires managing several relations between the performer and environment to strike an object while using the optimal effort needed to accomplish the goal. Relevant features of the performer include physical capabilities related to anatomy, morphology, and movement coordination, all of which can be expected to vary as a function of age. We predicted that older children compared to younger children would strike more accurately and with greater downward velocity, and would exhibit greater motion of the elbow and wrist. Relevant features of the environment include the physical properties of the hammer, the substrate and the object to be struck. In this study, we manipulated the physical properties of the hammer provided to the children to hammer a cylindrical peg into a pegboard. We predicted that the children would strike more often with the hard side of the hammer head toward the peg when given a hammer with hard and soft surfaces, and we expected that older children would do so more reliably than younger children. Finally, we predicted that children would achieve greater displacement of the hammer and strike with greater velocity when using a hammer with a handle than one lacking a handle, although we expected that they would be less accurate when striking with a handled hammer. We also examined the

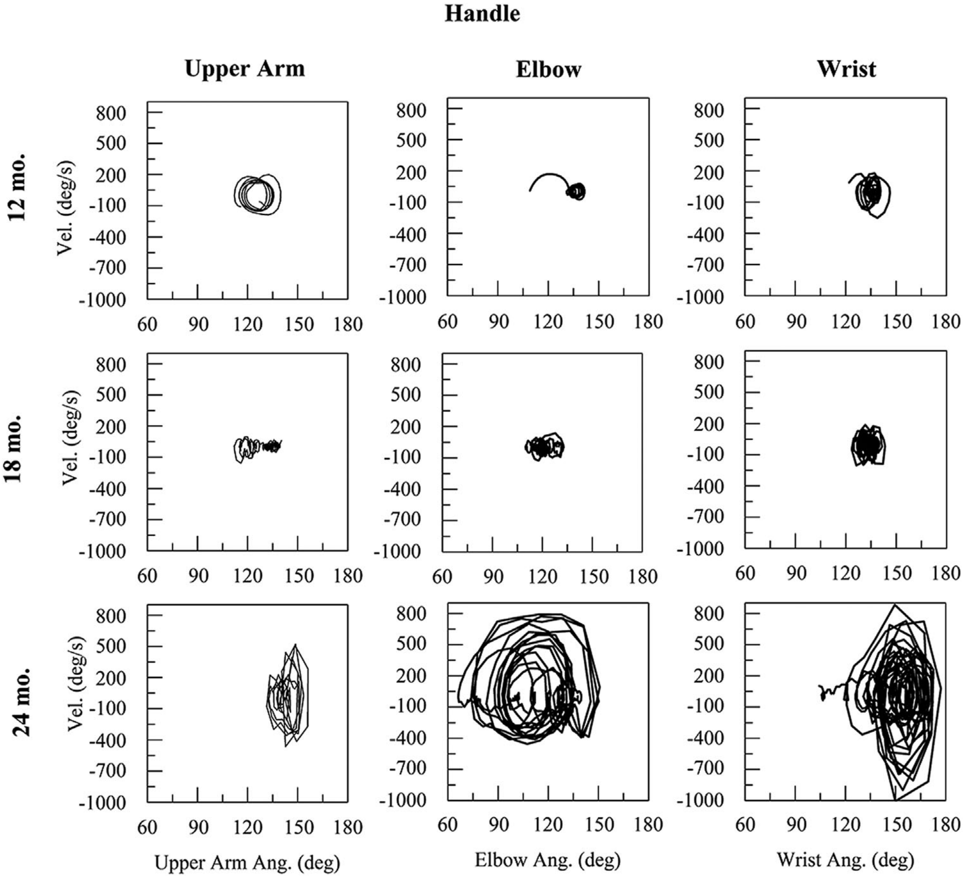

FIGURE 7 Phase-plane plots for HANDLE trials for one representative child per age group

different sitting positions displayed by the children, to assess variety and stability of posture.

Children 12–24-months old displayed the foundational elements of hammering: they struck hard surfaces with the hammer and typically held the object by the handle when a handle was present. Posturally, children usually sat while hammering, adopting positions providing a stable base of support. A greater proportion of younger children than of older children straddled the platform with both legs outstretched on the floor. This observation may reflect better postural control among the older children, who could maintain their balance in positions that provide a relatively smaller base of support. The relation between postural control and the performance of vigorous percussion by individuals of different morphology and body mass deserves further investigation.

4.1 | Sensitivity to affordances and allocentric frames of reference

As predicted by the ecological view of the development of tool use (Lockman, 2000), children in their second year of life were sensitive to the affordances of their striking actions and of the objects that they used to strike a peg. Children struck the peg more often with a handled hammer than with a non-handled hammer (a cube) held in the hand. They struck the peg more often with a rigid surface than with a soft surface, and they were less likely to push the hammer on the peg when the rigid surface faced it, compared to the soft surface. These results parallel Bourgeois et al.'s (2005) findings that children between one and two years of age adaptively adjust a goal-directed action (striking a surface) in accord with the properties of the held object to maximize the affordances related to percussion.

We found that children struck with the rigid surface of the hammer on their first strike more often than expected by chance when they used the handled hammer, but not when they used a hammer without a handle. This could indicate expanding anticipatory orientation of an object with respect to another object. Alternatively, it might reflect passive movement of the more rigid part of the cube, the wood side, downward if the child did not have a firm grip on the handle, so that the handle rotated slightly in the hand when he or she struck the peg or the pegboard with the head of the hammer. These movements would be less likely to occur with a hammer held directly in the hand, as the fingers closed around the sides of the hammer so that it could not rotate in the hand. The childrens' visual inattention to the hammer while they struck the peg, and the lack of reorienting the hammer head following a strike with the foam face suggest that children did not act in an anticipatory way to orient the wood side of the cube to the peg. Additional research is needed to distinguish among these possibilities, and to clarify in what manner children develop anticipatory positioning of a particular feature of a held object that will be used to contact another object. In some other studies, children within the same age range as this study did exhibit anticipatory positioning of a held object

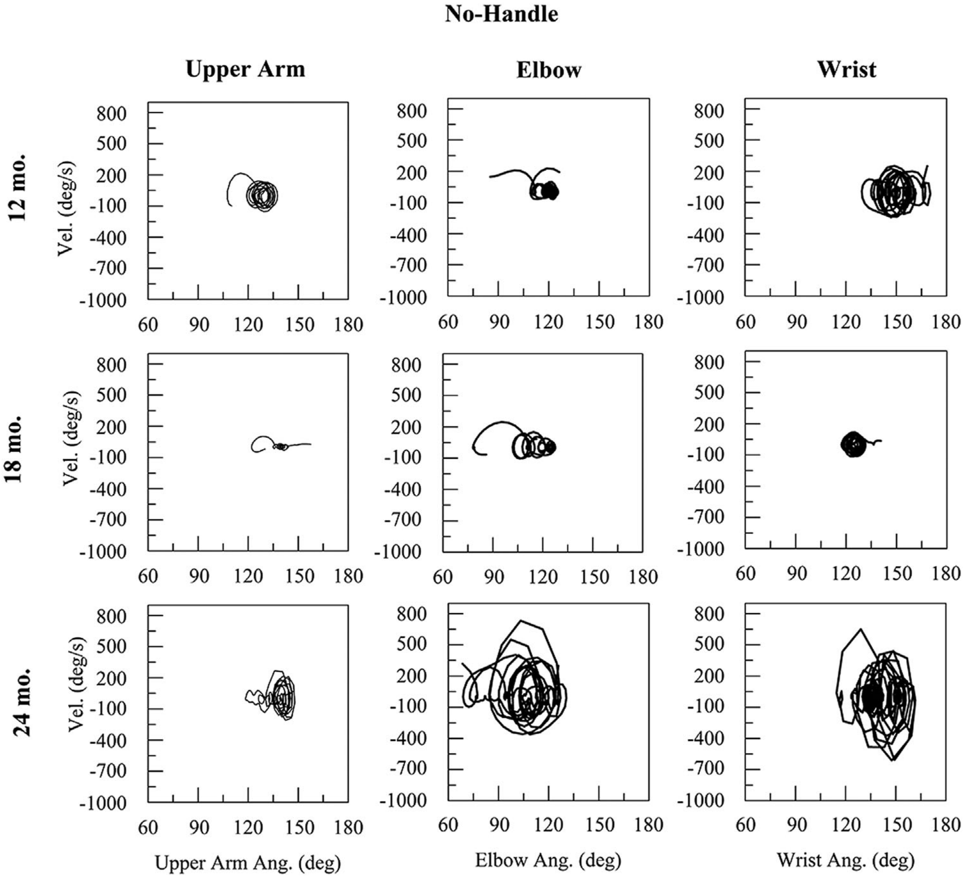

FIGURE 8 Phase-plane plots for NO HANDLE trials for one representative child per age group

in relation to another object. Street et al. (2011) show that 24-month-old children (but not 18-month olds) can orient a disk so that its long axis aligns with a slot, to insert the disk into the slot, and Fragaszy, Kuroshima, and Stone (2015) show that 2-year-old children can usually align a bar (one feature) and a cross-shaped object (two features) with a matching cut-out in a tray to insert the object into the cut-out but do not manage to align an object with three features, whereas 3-year olds can complete this last task. The handled hammer presents an option to orient a particular surface to another surface, but does not require that orientation to achieve the goal of striking the peg. It appears that children between 12 months and 2 years of age ignore the orientation of the hammer head to the peg, and concentrate instead on the striking action. The finding that the children were not particularly accurate with their strikes, missing the peg target on half to a quarter of strikes, depending on age (see also Kahrs et al., 2014), is another indication that the children made ineffective use of allocentric frames of reference while striking. Thus it appears that sensitivity to affordances of objects for percussion and potentially also anticipatory orientation of an object are dissociable from, and develop earlier than, accurate action with an object in support of effective percussion on another object. Perhaps postural demands influence deployment of attention to the hammer and/or to allocentric relations between the hammer and the peg.

That children produced strikes more often with the handled hammer than with the non-handled hammer is particularly interesting. Children used handled objects with interest and persistence even though they were less accurate at striking the peg with these objects than with the cubes lacking a handle. The handle altered the familiar spatial relation between the target object and the cube held in the hand. The cube was fixed at the end of a rigid segment, a few inches from the hand gripping the handle. The child holding a handled hammer must learn to manage an altered and less familiar spatial relation than when percussing objects held directly in the hand. Perhaps the challenge of managing this new relation appealed to the children, motivating their persistent activity with the handled hammer in spite of reduced accuracy, compared to when they struck the peg while holding the cube directly.

Our outcomes build upon Kahrs et al.'s (2012, 2013) observations of children 6–15 months old engaged in banging a cube held in the hand or a hammer using its handle. According to Kahrs et al., as children matured their banging actions became more controlled and efficient, evidencing increasing preparedness for instrumental tool use. Our task required children in their second year of life to engage in similar motor actions as those in Kahrs et al.'s studies, but within the context of instrumental tool use, with the addition of a peg that provided a target for hammering. Our findings are consistent with the developmental trajectory proposed by Kahrs et al. (2012, 2013), with 18- and 24-month olds evidencing more accurate strikes than the 12-month-old children. Similarly, Kahrs et al. (2014) report that, among children 19–35-months old, older children were more likely to complete a hammering task similar to the one presented in the current study. The manner in which children controlled their movements supported increasing accuracy as well as increasing velocity of strikes.

4.2 | Motor behavior-hammer kinematics, arm motions

Development in childrens' management of the altered spatial relations presented by the handled hammer is suggested by comparison of the youngest children in our study with children one year older. Twelve-month old children struck more frequently with handled than non-handled cubes, but they did not differentiate their actions (in terms of maximum displacement or velocity, or elbow or wrist flexion) with these two kinds of objects. In contrast, 24-month olds produced quite different actions with handled cubes than with non-handled cubes. They displaced the handled cube farther and swung it faster, producing higher downward velocity; hence, they increased the kinetic energy when using the handled cube compared to the plain cube. In contrast to 12-month olds, it appeared that 24-month olds used the handle to their advantage, raising the hammer higher in the air, thereby allowing gravity to transfer more potential energy into kinetic energy. Greater hammer displacement and velocity was produced by 24-month olds by increasing angular displacement and extension velocity of the elbow joint.

Our kinematic outcomes support the prediction that older children strike the peg with greater kinetic energy, particularly with a handled hammer. Older children achieved a significantly greater maximum downward velocity of the hammer using the handled hammer than the non-handled hammer. As the mass of the hammer was constant for a given hammer condition (and assuming, simplistically, that the mass of the hammer was the only mass involved in the hammer-peg collision) and kinetic energy = ½ mass × velocity^2, the hammer kinetic energy of the 24-month-old group, on average, was 3.7 times greater than that of the 12-month-old group.

With respect to arm motions, the developmental shift with age from moving the arm more about the shoulder joint relative to the other joints to proportionately greater motion about the more distal joints somewhat follows Dounskaia's (2005) "leading joint" hypothesis. Dounskaia proposed that, with practice, a multi-joint movement skill progresses from greater movement in proximal joints to more distal joints. A shift in the number of joints used and the degree of motion at each joint is displayed by individuals learning to knap stone, for example (Bril et al., 2010). Our findings that the oldest children in our study displaced the elbow farther than both groups of younger children, provide mixed support for the hypothesis that motor control develops from proximal to distal joints. Variation across ages was in the expected direction for the elbow, but not the wrist. These findings differ from those of Kahrs et al. (2014), who report that children 19–35 months old gradually increase proportional movement of the wrist during hammering with a handled hammer, but that they rely less on movement of the elbow with age. Perhaps the differences between the findings of the two studies reflect differences in the hammers used, the postural demands of the setting, or the force required to move the pegs in the two studies.

Our outcomes more closely support Swinnen, Maission, and Heuer's (1994) hypothesis linking changes in joint motions during skill development with previous experience. Swinnen et al. (1994) propose that the shift in joint motions and degrees of freedom utilized when adults learn motor tasks is dependent on the task and the bias toward using preexisting coordination patterns to accomplish similar tasks, whether they are suitable patterns or not. In their view, if there are fewer initial biases or the existing biases are not as predominant, then performance is less constrained. With learning, consistent movements develop as the various degrees of freedom come "under control" (p. 21). Possibly 12-month-old children in our study were biased toward using similar arm actions to those of banging objects, a familiar and well-practiced task (Kahrs et al., 2013), but because of less experience, they may have had less bias toward using one particular strategy than the older children. Certainly, the older children displayed, qualitatively, more consistent movements (more similarity of phase-plane portrait patterns among strikes) and accuracy. Hammering accurately is a challenging task, and the process of improving accuracy likely requires considerable experience. Vernooij, Mouton and Bongers (2012) pointed out that seated adult participants hardly improved their performance (i.e., did not improve their accuracy, as they did not adapt the direction they struck a target on a force plate using a hammer stone) over 5 days of practice, striking 60 times per day. They suggested that participants were still exploring the solution space of the problem even after 300 strikes. We are reminded by these findings that hammering with accuracy and force is a challenging task, even for adults.

One potential reason that accuracy improved with age is the tendency of individuals to self-organize movements. Adults naturally organize their hammering movement into a rhythmic pattern of oscillations about the upper extremity joints, using movement synergies that are frequency- and relative phase-locked (Turvey & Carello, 1996). Interestingly, our hammering frequencies for the handled conditions overlapped (range: 2.2–4.0 cycles $\cdot$ s^{-1}) the average fundamental frequency of the hammer (2.2 cycles $\cdot$ s^{-1}) in Turvey and Carello's study, in which the adult participants used typical claw hammers. Moreover, the cycle frequencies for non-handled compared to handled hammers did not differ consistently with age in our study, suggesting that this group of performers was naturally attracted to using a low bandwidth of hammering frequencies, regardless of the presence of a handle.

We have portrayed the progression of motor patterns in young children from less to more biomechanically effective when using a hammer, through adding additional degrees of freedom to the movement by the increased involvement of more distal joints. The increased angular displacements and phase plane plots suggest that older individuals used increased motions and velocities.

5 | CONCLUSION

Hammering is a natural action for young children; even very young children make appropriate use of a handle and are sensitive to its presence and to the hardness of the mallet as it strikes a surface. However, maintaining percussive accuracy, orienting the head of the hammer in an anticipatory manner, and involving more than one joint in the striking motion challenge young children between the ages of 1 and 2 years. Hammering is, therefore, a useful natural action through which to study developing motor skills in a tool-using context. It also offers the opportunity for interesting comparative studies, as some species of nonhuman primates also use percussive tools skillfully, in the same sense as "skill" is applied to percussive tool use in humans (Bril et al., 2010; Fragaszy, Liu, Wright, Allen, & Brown, 2013; Mangalam & Fragaszy, 2015).

It will be particularly interesting to investigate the development (and possibly re-organization) of skill in hammering in relation to changes in postural control, body size and shape, and neural functioning. All of these aspects of function are changing concurrently in early childhood (Corbetta & Bojczyk, 2002; Johnson-Frey, 2004), and we do not yet understand the synergy among them. Advancement of developmental theory in this domain requires a broad interdisciplinary effort, to which this study contributes, even though the findings of our study are limited by the size of our sample and the resolution of measurement that we achieved. No doubt future studies can improve on both of these dimensions of the work.

Biryukova and Bril (2008) suggest that energy optimization can serve as an index of expertise, and changes in energy optimization reflect the learning process. This view suggests that it would be useful to study the kinetics of hammering in young children as a vehicle to study the development of skill in this form of tool use. This study joins work by Kahrs et al. (2012, 2014) to support this suggestion. Kahrs et al. (2012) report that between 7 and 14 months of age, children decrease the velocity and increase the straightness of their strikes with a held object, preparing them for instrumental tool use. We show that children in the second year of life begin to increase the use of the elbow in striking. Kahrs et al. (2014) show that children 19–35 months old increasingly make use of the wrist in striking with a handled hammer, particularly when using their dominant hand, and slow down their strikes following a missed strike. Fitzpatrick et al. (2012) found that movement amplitude with a hammer increased across 2–4 years of age, but that 4-year olds were less able than adults to adjust movements to tools with different properties. Development of other features of skilled hammering remain to be investigated. Further study of this ancient and ubiquitous skill will provide useful information to researchers in several fields.

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