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The Development of Tool Use: Planning for End-State Comfort

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Some grips on the handle of a tool can be planned on the basis of information directly available in the scene. Other grips, however, must be planned on the basis of the final position of the hand. "End-state comfort" grips require an awkward or uncomfortable initial grip so as to later implement the action comfortably and efficiently. From a cognitive perspective, planning for end-state comfort requires a consistent representation of the entire action sequence, including the latter part, which is not based on information directly available in the scene. Many investigators have found that young children fail to demonstrate planning for end-state comfort and that adultlike performance does not appear until about 12 years of age. In 2 experiments, we used a hammering task that engaged children in a goal-directed action with multiple steps. We assessed end-state-comfort planning in novel ways by measuring children's hand choice, grip choice, and tool implementation over multiple trials. The hammering task also uniquely allowed us to assess the efficiency of implementation. We replicated the previous developmental trend in 4-, 8-, and 12-year-old children with our novel task. Most important, our data revealed that 4-year-olds are in a transitional stage during which several competing strategies were exhibited during a single session. Preschoolers changed their grip within trials and across trials, indicating awareness of errors and a willingness to sacrifice speed for more efficient implementation. The end-state-comfort grip initially competes as one grip type among many but gradually displaces all others. Children's sensitivity to costs and drive for efficiency may motivate this change.

Keywords: tool use, action planning, end-state comfort, motor development, manual skills

Planning is a crucial component of problem solving and an important marker of cognitive development. Planning in simple tasks (e.g., pulling a blanket to grasp an out-of-reach toy) begins in infancy. In more complex problem-solving tasks, younger children typically perform worse than older children. But aside from establishing that planning is possible in infancy and improves with age, researchers know little about the development of planning within individual children or across age groups. To study the development of planning, researchers need a task with multiple steps in a hierarchical organization, a task with a motivating and obvious end point that can be reached by different routes but with one route clearly superior. Such a task allows children to choose different strategies across trials and to make mistakes within trials and correct them. By observing this process, researchers can establish the most effective mode of implementation to achieve the goal, the extent of preliminary planning before action is taken, the extent of intraindividual variability across trials, and the developmental progression in planning as children figure out the most effective strategy. Tool use is a "royal road" in the study of planning in children because it meets these requirements (Keen, 2011). Here, we investigated the development of motor planning by asking children to hammer a peg in the context of an "end-state comfort" task.

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Planning for End-State Comfort

Tool use, such as wielding a hammer, involves cognitive components for planning actions adaptively (Keen, 2011; Rosenbaum et al., 1990). For example, adults typically grasp a water glass with their thumb pointing up. But when flipping an upside-down glass to fill it with water, their initial grip is atypical: The thumb initially points down so that after flipping the glass, the thumb comfortably points up (see Figure 1A). Rosenbaum et al. (1990) dubbed this phenomenon the *end-state comfort effect* because the initial *start-state* grip is unusual and uncomfortable, but it allows for a smooth transition to a more efficient and comfortable end-state position. At the moment of the initial grip, the end state is not directly available to perception. Thus, the initial thumb-down grip position reflects a plan for a sequence of actions that has the end state in mind.

Likewise, in laboratory studies, adults have used initially atypical or awkward start-state grips so as to end with more typical and efficient end-state grips (Rosenbaum, Chapman, Coelho, Gong, &

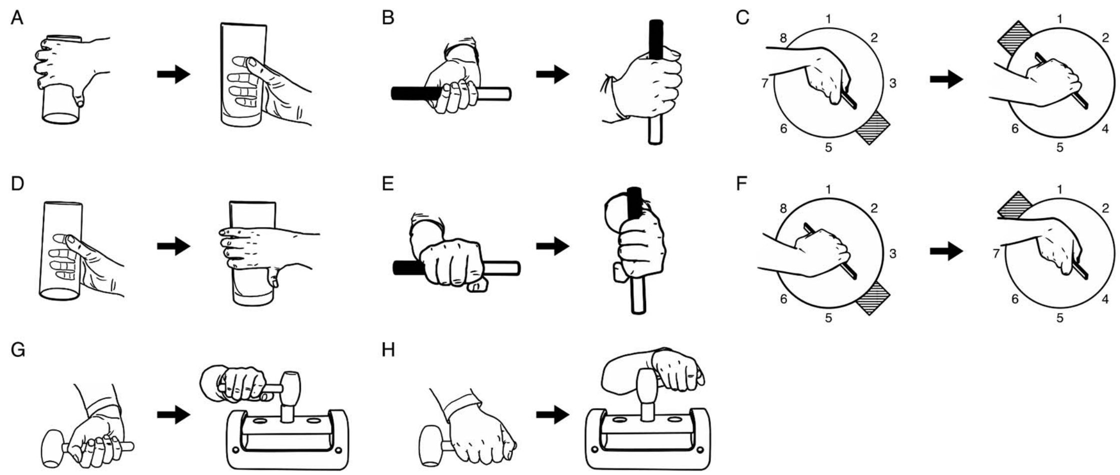

Figure 1. Hand configurations for initial grip and implementation. The left side of each panel shows the initial hand configurations consistent with end-state comfort (Panels A, B, C, and G) or start-state comfort (Panels D, E, F, and H). The right side of each panel shows the subsequent implementation of the object. Panel A: Initial thumb-down grip that allows for a comfortable thumb-up grip while filling the glass. Panel B: Initial underhand grip that allows for a comfortable thumb-up grip while placing the dowel. Panel C: Highly torqued initial grip that allows for a comfortable ending grip while turning the handle. Panel D: Initial thumb-up grip that leads to an uncomfortable thumb-down grip while filling the glass. Panel E: Initial overhand grip that leads to an uncomfortable thumb-down grip while placing the dowel. Panel F: Minimally torqued initial grip that leads to a highly torqued and uncomfortable grip while turning the handle. Panel G: Initial underhand, radial grip that allows for hammering with the iconic method. H: Initial overhand, ulnar grip that leads to implementing the hammer with an awkward grip.

Studenka, 2013; Rosenbaum, Chapman, Weigelt, Weiss, & van der Wel, 2012). In the classic horizontal dowel task, right-handed adults used an overhand grip to turn the dowel vertical when the task was to place the right end of the dowel on a target; consequently, the thumb pointed up in the end-state position. But when the task was to place the left end of the dowel on the target, right-handers used an underhand grip to maintain the same, presumably more comfortable, thumb-up end state (Rosenbaum et al., 1990; Short & Cauraugh, 1997; see Figure 1B). Similarly, in a handle-rotation task, adults spontaneously used an initially awkward start-state grip to ensure a comfortable end-state position with minimal torque on the wrist and elbow (Rosenbaum, van Heugten, & Caldwell, 1996; see Figure 1C). Adults also consistently showed the end-state comfort effect in several other paradigms (Cohen & Rosenbaum, 2004; Cowie, Smith, & Braddick, 2010).

In contrast to adults, young children seem largely oblivious to end-state comfort (Wunsch, Henning, Aschersleben, & Weigelt, 2013). When the task is to turn over an upside-down cup and fill it with water, young children rarely grasp the cup so that they can end in the comfortable thumb-up position. Instead, they begin with a comfortable start-state position and end in a presumably awkward thumb-down position (Adalbjornsson, Fischman, & Rudisill, 2008; Knudsen, Henning, Wunsch, Weigelt, & Aschersleben, 2012; Scharoun & Bryden, 2014; see Figure 1D). Even children who set the table before every meal at school fail to consistently show end-state comfort grips (Robinson & Fischman, 2013). Likewise, in the classic horizontal dowel task, children do not consistently display end-state comfort grips until at least 9 years of age (Hughes, 1996; Manoel & Moreira, 2005; Smyth & Mason, 1997; Stöckel, Hughes, & Schack, 2012; Thibaut & Toussaint, 2010; Weigelt & Schack, 2010); instead they persist with an overhand grip regardless of dowel direction, resulting in a presumably uncomfortable thumb-down position (see Figure 1E). Similarly, in the handle-turning task, children are still not at adult levels by 8 years of age (Smyth & Mason, 1997; Wilmut & Byrne, 2014); young children grasp the handle with their thumbs pointing toward the starting position, regardless of end position (see Figure 1F).

Given children's poor performance in these end-state comfort tasks, researchers have frequently referred to trials requiring an initial overhand or thumb-up grip position as "easy" or "simple" trials and those requiring an initial underhand or thumb-down grip position as "difficult" or "advanced" trials (e.g., Jovanovic & Schwarzer, 2011; Stöckel et al., 2012; Thibaut & Toussaint, 2010). Thus, changing the direction of the handle of a tool from trial to trial presents a challenge. In a hammering task, when the handle points to the dominant hand, it is in the easy position because children will grasp the handle with an overhand radial grip (thumb toward the action end) with their dominant hand—the end-state comfort grip for hammering. When the handle points to the nondominant hand, a reach with the dominant hand needs an underhand grip to maintain the radial orientation (see Figure 1G). The initial grip on the handle reveals whether the child has planned ahead for the pounding action. An initial ulnar grip (thumb away from the head of the hammer as in Figure 1H) left unchanged would lead to a presumably awkward ulnar grip during implementation. So selecting an underhand radial grip initially or changing an ulnar grip to a radial grip before pounding the peg indicate foresight in the difficulty looming for the ulnar grip. If a child displays a variety of grips over trials, this would suggest a state of transition in which different grips compete (Siegler, 1994; Stöckel et al., 2012).

Studies of end-state comfort in children typically focus on the age at which children first show the phenomenon and the age at which they consistently use the end-state grip like adults. Typically, each child receives only one or a few trials in the difficult condition and the data are reported as the percentage of children at each age showing end-state comfort. In reviewing the literature, Wunsch et al. (2013) noted inconsistent findings across 13 studies and suggested that task factors such as number of action steps, motivation, and familiarity with the task could affect results. Overall, it appears that only a few preschool-age children show end-state comfort in only a few tasks, and evidence of end-state planning becomes consistent across a great many tasks by 10 to 12 years of age. However, the age when children use end-state comfort grips is only a small glimmer of what end-state tasks could reveal, and group percentages conceal the developmental process by which end-state comfort is acquired.

End-state comfort tasks require children to represent complex relations between the hand, its grip on the tool, and the subsequent action to be performed with the tool to achieve a goal. Performance of end-state comfort grips may be related to children's cognitive representation of hand postures. For example, children who discriminated better among photographs of various grips showed more end-state comfort grips in a bar transport task, suggesting that cognitive representation plays an important role in children's planning of hand postures (Stöckel et al., 2012). Poor performance in end-state comfort tasks may reflect either inconsistent representations of the sequence of actions leading to the goal or a failure to represent the goal action itself. If the former, then children should be inconsistent in their *initial grips;* they should sometimes exhibit end-state comfort grips and other times not. Although some studies have found high consistency in initial grips across trials (Hughes, 1996; Thibaut & Toussaint, 2010; van Swieten et al., 2010), others have found profound intraindividual variability from trial to trial (Keen, Lee, & Adolph, 2014; Stöckel & Hughes, 2015). Unstable representations of the goal action with the tool should adversely affect the consistency of children's grips during *implementation*—regardless of how they initially gripped the tool. Young infants, for example, frequently try to eat from a spoon using an ulnar grip (pinky toward the bowl of the spoon as in Figure 1H), causing the food to spill as they bring the spoon to their mouth (Connolly & Dalgleish, 1989; McCarty, Clifton, & Collard, 1999). Toddlers switch from an initial ulnar grip to a radial grip midtrial, indicating the ability to correct an impending faulty implementation of the tool during the goal action (McCarty et al., 1999). Unfortunately, grips used for implementation and changing grips prior to implementation have been largely ignored or prohibited in studies of end-state comfort with preschool-age children. Most studies had only a few trials per child in the difficult condition, so the evidence regarding intraindividual variability is cloudy. The current studies respond to the need to evaluate behavior during the entire action sequence over many trials for each child.

Another possible reason for children's poor performance is that an "uncomfortable" or "inefficient" grip for an adult may feel fine to a child. Whereas adults avoid end states with uncomfortable torque on the wrist, children are willing to twist their wrists more than are adults when the only action is to grab a handle—so start-state and end-state comfort are identical (Kent, Wilson, Plumb, Williams, & Mon-Williams, 2009). Indeed, children frequently enjoy motor actions that adults deem inefficient and uncomfortable (taking long steps to avoid cracks in the sidewalk, playing Twister). Whereas adult participants assume that efficiency is integral to achieving a goal (Schmidt & Lee, 2011), children often do not (Adolph, Cole, & Vereijken, 2015). Instead, children may be motivated to explore different ways of handling a new tool, especially when the handle points away from their dominant hand (Wunsch et al., 2013). If children differ from adults in what they deem comfortable or are not concerned with implementing the tool comfortably or efficiently, then they should not adjust their grip after the initial grip. Changing their initial grip before performing the goal action would indicate that children share adult's concern for ending comfortably.

Moreover, efficiency is a meaningful construct only when one action is superior to another. To bring a loaded spoon to the mouth, children need to grasp the handle with their thumb near the bowl (similar to the right panel of Figure 1G); with an ulnar grip (as in Figure 1H), the food spills (McCarty et al., 1999). Most studies, however, have not quantified successfully accomplishing the goal (e.g., successfully filling the glass with water or bringing food to the mouth with a spoon) and have not compared measures of efficiency (e.g., number of movements, speed, variability of strategy selection) for start-state and end-state grips. Young children's manual skills are generally clumsy, and end-state comfort positions may be just as inefficient as are start-state comfort positions. Differences in implementation can provide evidence about efficiency, but most studies have not reported data on implementation or have not involved tasks where the tool required implementation after the initial grip.

Current Studies

In two studies using a hammering task, we investigated why young children fare so poorly on end-state comfort tasks. We observed children from 4 to 12 years of age, spanning the critical developmental period established in previous studies (Keen et al., 2014; Stockel et al., 2012; Weigelt & Schack, 2010; Wunsch et al., 2013).

We designed the studies to obtain multiple measures of children's planning, error detection, and efficiency as they tackled the same problem repeatedly. Hammers are a common toy for young children (Kahrs, Jung, & Lockman, 2014), and hammering down a peg is an obvious, self-evident goal. In fact, the hammering task was so enjoyable that we easily obtained 20 trials from each child, allowing robust analyses of intraindividual variability. The primary outcome measure was whether children showed evidence of planning for end-state comfort based on the initial grip and the grip used for implementation. Presumably, the most efficient and comfortable way to implement a hammer is by holding the handle in the dominant hand with the radial, overhand grip pictured in the right side of Figure 1G—what we call the *iconic hammering method*. Thus, on difficult trials (when the handle points away from the dominant hand), an end-state comfort grip would require initially grasping the handle in the dominant hand with the underhand, radial grip pictured in the left side of Figure 1G. However, it is possible that young children hammer as efficiently with their nondominant hand or with an ulnar grip as they do using the iconic hammering method, and it is possible that children do not find these non-iconic methods to be uncomfortable. Thus, to assess comfort, we reported children's grip position while implementing the hammer, not merely during the initial grip. Non-iconic methods for implementation would suggest either that children have a different notion of "comfort" than do adults or that they are unable to correct their grip to be more comfortable. To assess efficiency, we analyzed children's hammering on each trial (number of strikes to flatten the peg, percentage of strikes that missed the peg, and time lost due to changing grips) while using the iconic hammering method and the non-iconic methods.

Overall, planning consistent with the adult view of comfort and efficiency would entail an initial end-state comfort grip and implementation with the iconic method. Poor planning for end-state comfort, on the basis of the adult view of comfort and efficiency, would be evidenced by an initial grip inconsistent with end-state comfort and a change to the iconic method.

We also addressed several open questions regarding children's ability to plan for end-state comfort. To investigate the stability of children's representations, we reported intraindividual variability across easy and difficult trials. We compared children's performance when they were allowed to use their nondominant hand (Experiment 1) and when they were not (Experiment 2). Most previous work permitted children to use only their dominant hand (e.g., Jongbloed-Pereboom, Nijhuis-van der Sanden, Saraber-Schiphorst, Crajé, & Steenbergen, 2013; Smyth & Mason, 1997; Weigelt & Schack, 2010), and studies that allowed use of either hand did not permit children to change their initial grip (e.g., Manoel & Moreira, 2005; Stöckel et al., 2012). To determine how children would behave in a more ecologically valid setting, in Experiment 1 we allowed children free use of either hand throughout the session—just as when they are playing in their daily life.

Experiment 1: Hammering Using Either Hand

In Experiment 1, we asked 4-, 8-, and 12-year-olds and a comparison sample of adults to grasp a hammer to pound down a peg over 20 trials. Participants had both hands free. Of particular interest was whether children would show developmental differences on difficult trials in the frequency of initial grips that reflected end-state comfort (the underhand, radial grip with the dominant hand pictured in the left side of Figure 1G), whether the grip while implementing the hammer to pound the peg was consistent across ages, and whether children would display intraindividual variability in either the initial grip or the grip during implementation. High levels of intraindividual variability in initial grip on difficult trials would suggest that children entertain competing responses because none seem obviously "correct." In other words, children have difficulty figuring out how the initial action will affect the final action. Changing from an initial grip that is inconsistent with end-state comfort (e.g., the ulnar grip pictured in Figure 1H) to the iconic hammering grip for implementation (the overhand, radial grip pictured in the right side of Figure 1G) would suggest that children realize their mistake and are able to correct it before the goal action. Conversely, maintaining a grip inconsistent with end-state comfort throughout the trial would suggest that either children hold a different opinion about what is comfortable or they do not have the ability to correct their mistake. Finally, intraindividual variability during implementation would indicate that either children have unstable representations of the iconic hammering method or their goal is more geared to exploration than to efficiency.

Method

Participants. Because we expected the youngest children to show more variability in grip selection, we recruited a larger number of 4-year-olds than the older ages. In total, 54 children and eight adults participated: twenty-eight 4-year-olds (M = 4.20 years; 16 girls), thirteen 8-year-olds (M = 8.16 years; seven girls), thirteen 12-year-olds (M = 12.32 years; nine girls), and eight college-age adults (M = 21.14 years; four women). Children's families were recruited through advertisements and visits to maternity wards of local hospitals, and adults were recruited through word of mouth. Most participants were White and middle class. Children and their families received a photograph magnet and tote bag as souvenirs of participation. Adults received a small monetary payment.

We determined hand dominance on the basis of five measures: which hand participants reported using (right, left, either) to brush their teeth, cut with scissors, and hold a spoon or fork and laboratory observations of which hand they used to cut a circle shape with scissors and to draw a line between two targets (two trials with each laboratory task). Parents of the 4-year-olds reported their children's hand use for toothbrush, scissors, and spoon or fork, and the older children and adults answered for themselves. For each task, the experimenter scored use of the right hand as 0, left hand as 1, and either hand as 0.5. We calculated hand dominance on the basis of the average score over the five items. Average scores of 0 were considered right-handed, scores of 1 were considered left-handed, and scores between 0 and 1 were considered ambidextrous. Most participants were right-handed (71% of 4-year-olds, 85% of 8-year-olds, 83% of 12-year-olds, and 88% of adults); four children were left-handed (4% of 4-year-olds, 8% of 8-year-olds; and 15% of 12-year-olds); and eight children (25% of 4-year-olds and 8% of 8-year-olds) and 1 adult were ambidextrous. Data from the nine ambidextrous participants were not analyzed further. In addition, data were excluded from one 4-year-old who would not sit in the chair and from one 12-year-old who did not take the task seriously. Thus, the total sample was composed of twenty 4-year-olds, twelve 8-year-olds, twelve 12-year-olds, and seven adults.

Apparatus and procedure. Participants sat at a small table facing the experimenter. The experimenter lifted a screen to reveal a wooden hammer and pegboard located at midline and within arms' reach. She asked the participants "to pound the peg with the hammer until the peg is flat." The peg had a face diameter of 2.5 cm and protruded about 3 cm above the pegboard. The hammer had a 12.5-cm wooden handle and a cylindrical hammerhead with a length of 6.5 cm and a face diameter of 2.5 cm (see Figure 1H). The hammer rested on two blocks placed 16.5 cm apart, so that participants could easily use either an overhand or underhand grip to grasp the handle. The experimenter presented two blocks of 10 trials each, for a total of 20 trials. Within each trial block, the hammer was presented with the handle pointing to the right on five trials and the handle pointing to the left on five trials, with presentation order randomized. Between blocks, children performed the lab measures of handedness.

Sessions were videotaped at 30 fps from two camera angles: an overhead view and a side view of the child's face, arms, and upper body. The two views were mixed online onto a single video frame. Videos are shared on Databrary (www.databrary.org).

Data coding. Coders used Datavyu (www.datavyu.org), an open source, computerized video coding tool, to record the durations of particular events and the presence or absence of specific behaviors. A primary coder scored 100% of the data, and a secondary coder scored 50%–100% of each participant's trials to ensure interrater reliability. Coders agreed on 95%–100% of instances for each categorical variable ($\kappa = .78–.98$); the correlation coefficients for latency to strike and number of strikes were $r(951) = .99$ and $r(951) = .99$, respectively. Disagreements between coders were resolved through discussion.

To assess planning, coders scored participants' behaviors from the moment the screen lifted until the video frame when participants wielded the hammer for the first strike. During this period, participants decided which hand to use; how to grasp the hammer; and if necessary, how to reconfigure their grip before striking the peg. Thus, coders scored initial *hand selection* (whether the right, left, or both hands first grasped the hammer), *radial or ulnar grip* (thumb closest to the hammer head or thumb farthest from the hammer head), *over- or underhand grip* (palm facing down toward the table or up), and whether participants *changed their grip* (from the initial grip of the handle to the grip used to hammer the peg; see left panels of Figure 1G and 1H).

To assess implementation of the hammer, coders scored participants' behavior after the planning period—from the moment of the first strike with the hammer until the peg was pounded down completely. Thus, for each strike within each trial, coders scored *hand selection, radial or ulnar grip,* and *over- or underhand grip* as just described (the right panels of Figure 1G and 1H) and *handle orientation* (whether children held the hammer handle horizontally or vertically relative to the table). To assess efficiency, coders scored whether the participant *missed the peg* at least once during each trial (hammer did not touch the peg) and the total *number of strikes* (up–down movements, including misses) within a trial until the participant flattened the peg.

Results and Discussion

To examine planning for end-state comfort, we recoded handle direction from right or left to easy (handle pointing toward dominant hand) or difficult (handle pointing toward nondominant hand). We used a 4 (age group: 4-, 8-, or 12-year-olds or college-age adults) × 2 (condition: easy or difficult) series of mixed-design analyses of variance (ANOVAs) on each outcome measure, with Sidak-corrected post hoc comparisons between easy and difficult conditions for each age group. Preliminary analyses showed no effect of trial block or gender, so these factors were excluded from further analyses. All analyses used the standard alpha value of .05.

Overall, children appeared delighted with the hammering task. Every child grasped the hammer within a few seconds, completed all trials, and hammered the peg down on every trial.

End-state comfort. On easy trials, action plans were nearly uniform: Participants at every age used their dominant hand with an overhand, radial grip (see filled circles in Figure 2A). Difficult trials presented a different story. Adults uniformly used their dominant hand with an underhand, radial grip (see the left side of Figure 1G)—the signature components of planning for end-state comfort. Similarly, 12-year-olds showed end-state comfort on $M = 91\%$ of difficult trials. In contrast, 8-year-olds showed end-state comfort on $M = 76\%$ of difficult trials, and 4-year-olds showed end-state comfort grips on only $M = 38\%$ of difficult trials (see filled triangles in Figure 2A). The ANOVA confirmed main effects for age and condition and an interaction between age and condition (see Table 1, top row); post hoc comparisons showed differences between easy and difficult conditions for 4- and 8-year-olds ($p < .001$ and $p = .046$, respectively). To investigate the developmental progression of end-state comfort, we examined children's propensity to show end-state comfort on difficult trials. The ANOVA revealed a significant effect of age, $F(3, 47) = 10.49$, $p < .001$, $\eta_p^2 = .85$. Post hoc analyses showed that 4-year-olds showed significantly less end-state comfort on difficult trials than did all of the other age groups (all ps $< .013$).

Moreover, on difficult trials, 4-year-olds were more likely to use their nondominant hand, use awkward ulnar grips, and change their grips than were older children and adults (see the filled triangles in Figure 2B–2D and rows 2–4 in Table 1). Post hoc comparisons confirmed differences between easy and difficult conditions for 4-year-olds for each measure (all ps $< .001$). Four-year-olds' use of the ulnar grip was surprising given that most 2-year-olds grasp a spoon with their nonpreferred hand rather than use an ulnar grip (McCarty, Clifton, & Collard, 2001). The ulnar grip indicates complete lack of adjustment in initial grip and lack of attention to handle direction. In contrast, an initial radial grip with the nondominant hand suggests attention to handle direction (McCarty et al., 1999), albeit not an adult grip strategy. Changes in grip strategy—regardless of whether the initial grip was ulnar with the dominant hand or radial with the nondominant hand—suggest that children recognize that their initial grip did not allow for a comfortable end state (McCarty et al., 1999).

As shown in Figure 3A–3C, younger children showed considerable inter- and intraindividual variability in initial grips in the difficult condition. Only 15% of the 4-year-olds showed end-state comfort grips on every difficult trial, 40% never showed evidence of end-state comfort, 45% used end-state comfort grips on some trials but not others, and 85% showed more than one type of initial grip. Intraindividual variability was reduced in the 8- and 12-year-olds (50% and 25% showed more than one initial grip, respectively) but did not disappear until adulthood. Notably, changing grips (from ulnar to radial and from nondominant hand to dominant) prior to the first strike was exceedingly common in children who failed to initially choose end-state comfort grips (see prevalence of cross-hatched bars in Figure 3A–3C). Directionality of grip change was almost uniformly from nonradial to radial. If one discounts the two-handed grips used by children who pushed the peg down rather than pounded it, 96% of changes from initial grip to striking grip were from nonradial to radial grip with the dominant hand. One explanation for individual differences in variability and the high frequency of changing grips is that children undergo a transitional period of development where end-state comfort planning is available but may not be prioritized.

Consistent with this explanation is our finding that children did not improve across trials. Learning within a session would be shown by high variability early on and more end-state-comfort grips later. However, 4-year-olds did not show a reliable increase in end-state comfort on difficult trials as the session progressed (see the filled triangles in Figure 4). A logistic regression predicting end-state comfort from trial number confirmed that 4-year-olds

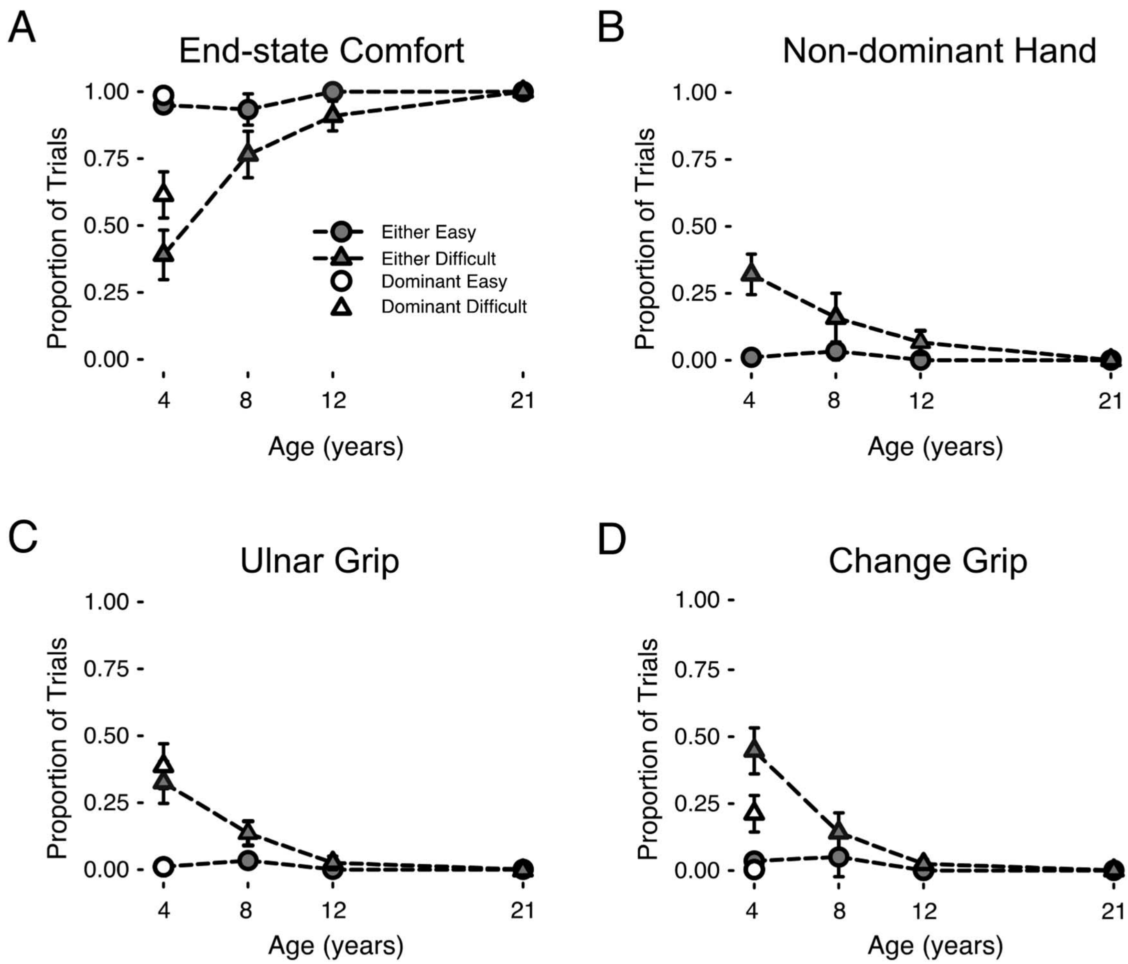

Figure 2. Average proportion of trials by age and condition for initial grips. Data from Experiment 1 (in which participants could use either hand) are represented with filled symbols; data from Experiment 2 (in which children could use only their dominant hand) are represented with open symbols. Note that Experiment 1 included four age groups (4-, 8-, and 12-year-old children and adults) and Experiment 2 included only 4-year-olds. Circles denote easy trials (handle pointed toward the dominant hand), and triangles represent difficult trials (handle pointed toward the nondominant hand). Initial grip consistent with end-state comfort (Panel A). Initial grips inconsistent with end-state comfort: grips with the nondominant hand (Panel B), ulnar grips (Panel C), and grips changed prior to implementation (Panel D). Error bars denote standard error. No data from Experiment 2 are shown for use of the nondominant hand, because children were not allowed to use their nondominant hand.

were no more likely to show end-state comfort on later than earlier difficult trials ($\beta = 0.04$), Wald's $\chi^2(1) = .64$, $p = .42$. Young children were variable in their initial grips throughout the session. Nonetheless, the lack of within-session learning may be due to the ease with which the initial grip could be changed, thereby obviating any penalty associated with grips that were not conducive to end-state comfort. It is possible that children planned for both start-state and end-state comfort on trials when they changed grips: The plan was to grasp the handle with a comfortable overhand grip in either hand and then to place it in the radial position in the dominant hand for implementation. Indeed, changes in grip strategy typically appeared smooth and seamless. However, as shown in the left panel of Figure 5, children took about a second longer from initial grip to strike on trials when they changed their grip compared with trials when they did not, $t(15) = 8.18$, $p < .001$. Children may not have viewed the cost of a lost second to be greater than the cost of using an initially awkward underhand grip.

Implementing the hammer. Like planning the initial grip, implementation grips were uniform in adults. On every trial, adults used an overhand, radial grip with their dominant hand while holding the handle parallel to the table and striking the peg with the hammerhead—the "iconic" use of a hammer (see the right panel of Figure 1G). In contrast, children did not use the iconic method exclusively, and they sometimes used multiple hammering methods within trials. They used their nondominant hand, hammered with an ulnar grip, held the handle vertically while striking with the top of the hammerhead, used two hands to strike the peg, or used the hammerhead to push the peg down. Nonetheless, the

Table 1
ANOVA Main Effects and Interactions for Participants in Experiment 1 (Hammering With Either Hand)

Variable	Age effect		Condition effect		Interaction	
	F	η_p^2	F	η_p^2	F	η_p^2
End-state comfort grip	8.19***	.34	23.19***	.33	11.15***	.42
Nondominant grip	2.97*	.16	11.21**	.19	4.00*	.20
Ulnar grip	5.99**	.28	9.25**	.16	6.08***	.28
Change in grip	6.66***	.30	12.82***	.21	9.28***	.37
Iconic method	4.56**	.23	4.96*	.10	.87	.05
Strikes per trial	3.17*	.17	.13	.00	.16	.01
Miss in a trial	12.72***	.45	.06	.00	.83	.05

Note. ANOVA = analysis of variance.
* $p \leq .05$. ** $p < .01$. *** $p \leq .001$.

iconic method was still children's strategy of choice: They used *only* the iconic method on $M = 76.6\%$ and 87.9% of trials for 4- and 8-year-olds, respectively (see Figure 6A), and overall, including mixed trials (that included iconic grips on some strikes and non-iconic grips on some strikes), they used the iconic method in $M = 85.4\%$ and 94.4% of bouts, respectively. Both 4- and 8-year-olds used the iconic method more frequently on easy than difficult trials, and the ANOVA confirmed main effects of age and condition (see Table 1, row 5). Post hoc comparisons revealed that 4-year-olds were less likely to use the iconic hammering method than were 12-year-olds and adults ($p = .02$ and $p = .03$, respectively). Given that 4-year-olds used the iconic method on most trials, we concluded that the iconic method was their preferred end-state and, therefore, that our definition of end-state comfort—an initial grip with the dominant hand that allowed for a radial grip—was appropriate across age groups.

Although some participants in each age group flattened the peg with one strike, adults hammered more efficiently than did younger children. Older children and adults never used more than 14 strikes to flatten the peg, and most of the time it took them less than six. Four-year-olds behaved differently: Twelve of the 4-year-olds used more than 15 strikes to pound the peg flat, and one child used 77 strikes in a single trial; the ANOVA confirmed only a main effect of age (see Table 1, row 6). Furthermore, adults never missed the peg during a hammer strike, but 4-year-olds missed on $M = 33.0\%$ of trials; the ANOVA revealed only a main effect of age (see Table 1, row 7), and post hoc analyses confirmed that 4-year-olds had more trials with at least one miss than did each of the other age groups (all ps $< .001$).

Given that 4-year-olds are relatively clumsy hammerers, it is possible that they did not benefit from using the iconic hammering method. Thus, we calculated the average percentage of trials with misses for children who used the iconic method at least once ($N = 20$ children) and for children who used a non-iconic method on at least one trial ($N = 15$ children). Notably, 4-year-olds showed no difference in strike number on trials with the iconic method ($M = 7.20$ strikes per trial) compared to trials with other methods ($M = 6.02$). Likewise, 4-year-olds were just as likely to miss the peg when they used the iconic hammering method ($M = 28\%$ of trials) as when they did not ($M = 32\%$ of trials). However, these null results should be interpreted with caution because the analysis relied on children's spontaneous use of different hammering methods, and several children contributed no or only a few trials with both hammering methods to the analysis, which excluded them from the non-iconic averages.

Summary of Experiment 1. Each age group showed levels of end-state comfort consistent with those in previous research. In particular, 4-year-olds on average showed end-state comfort on less than 50% of trials, despite performing an engaging task with a familiar tool. On difficult trials, most 4-year-olds displayed tremendous intraindividual variability in initial grips from trial to trial, revealing a range of competing responses. Although the majority of children displayed an end-state comfort grip at least once, and three always chose it, 40% of 4-year-olds never chose end-state comfort grips for the initial grip. The data in Figure 3A appear to be a snapshot of children at a transitional point of development.

Intraindividual variability in initial grips did not hold for implementation. Thus, it is unlikely that children's goal was more geared to exploration than to efficiency (Wunsch et al., 2013). Children had a clear preference for the iconic hammering method and frequently changed their initial grip to use the iconic method. Indeed, all of the 4-year-olds who never showed end-state comfort grips frequently changed their initial grip to use the iconic method. Preference for iconic hammering at all ages indicates that even the youngest children had the correct goal action in mind. The ease with which children were able to change grips may have influenced their hand postures, so children may have viewed the cost of an initially awkward end-state comfort grip as equivalent to the cost of changing from a comfortable start-state grip to an iconic hammering grip. Thus, cost equivalence presents an alternative explanation for high intraindividual variability, and the observed deficit in end-state comfort may not reflect a failure in 4-year-olds' actual planning abilities.

Moreover, we did not find evidence that 4-year-olds' use of the iconic hammering method was superior to implementing the hammer with the nondominant hand or with an ulnar grip. Thus, hammering grips that appear uncomfortable or inefficient to the adult eye may have been adequate from a child's point of view. That is, lack of an adultlike initial grip may not have hampered hammering in the 4-year-olds.

Experiment 2: Hammering With the Dominant Hand

We designed Experiment 2 to eliminate the cost-equivalence explanation for 4-year-olds' deficit in end-state comfort grips. In Experiment 2, we prohibited use of the nondominant hand: Children wore an oven mitt on their nondominant hand and were told to use only their dominant hand. More important, the oven mitt simultaneously increased the cost of changing from an ulnar to iconic hammering grip because preventing use of the nondominant hand made it difficult and cumbersome to "correct" an initial grip. Together, these manipulations allowed us to test whether the low levels of end-state comfort in Experiment 1 resulted from children's ability to smoothly and quickly change their initial grips. If children are sensitive to efficiency, the increased time cost of corrections in Experiment 2 should result in fewer corrections and more end-state comfort grips. Alternatively, frequent use of an ulnar grip (see the left side of Figure 1H) in Experiment 2 would provide conclusive evidence that 4-year-olds are not attending to handle direction, are not planning to achieve end-state comfort by

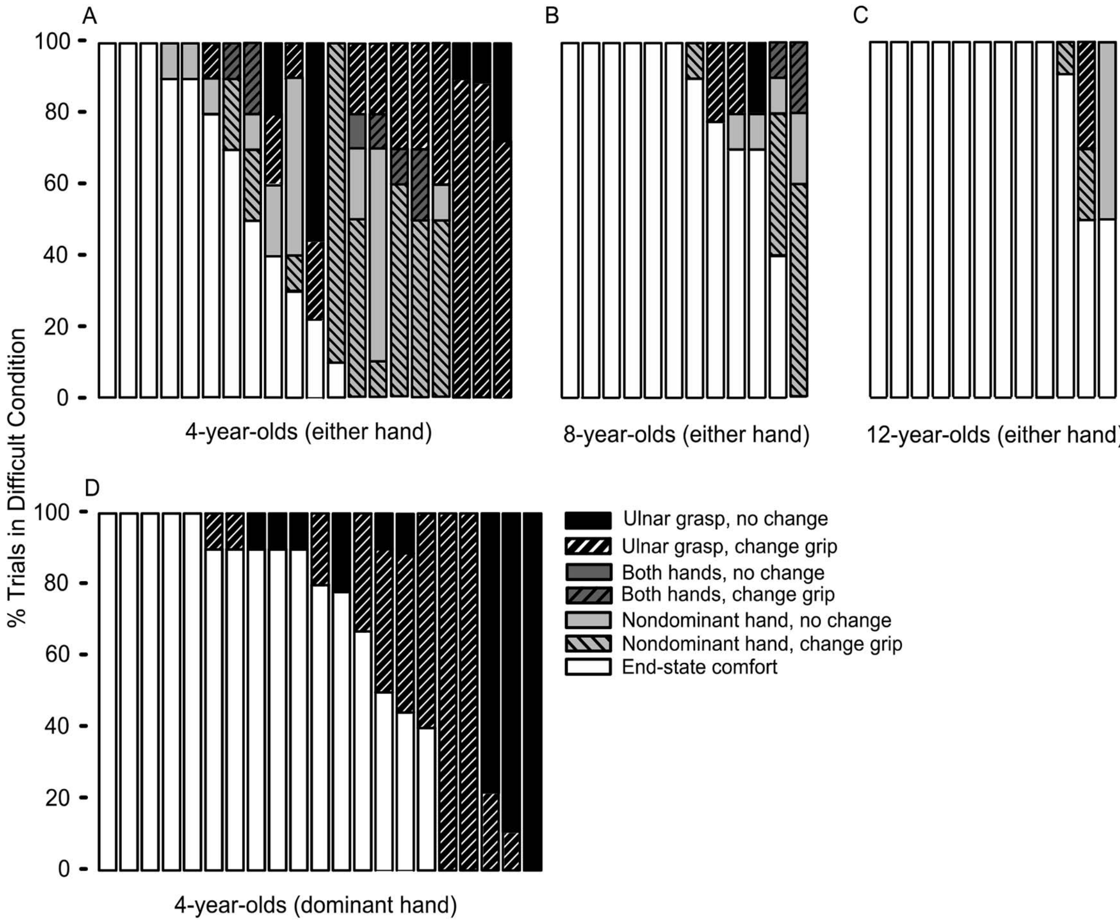

Figure 3. Stacked bar graphs illustrating intraindividual and between-groups variability in initial grip on difficult trials for Experiment 1 (top row) and Experiment 2 (bottom row). Note that Experiment 1 included four age groups (4-, 8-, and 12-year-old children and adults) and Experiment 2 included only 4-year-olds. Adults are not shown, because they displayed only end-state comfort grips. Each bar represents one participant. White bars show end-state comfort grips, black bars show ulnar grips, dark gray bars show grips with both hands, and light gray bars show grips with the nondominant hand. Striped bars represent change in grip before striking the peg. In Experiment 1, seven grips were possible: ulnar grips with and without a change in grip strategy, nondominant grips with and without a change in grip strategy, grips with both hands with and without a change in grip strategy, and end-state comfort grips. In Experiment 2, only three grip strategies were observed: ulnar grips without a change in grip strategy, ulnar grips with change in grip strategy, and end-state comfort grips.

changing grips, and have not represented the sequence of actions required for hammering with the iconic method. In addition, we wanted to follow up on the hint in Experiment 1 that iconic hammering did not benefit 4-year-olds. Rather than relying on children's spontaneous use of non-iconic hammering methods to assess their efficiency relative to the iconic method, at the end of the session we systematically asked all children to hammer with their nondominant hand and with an ulnar grip to compare the efficiency of different methods on a set number of trials.

Method

Participants. We tested twenty-four 4-year-olds ($M = 4.02$ years), recruited as in Experiment 1. Most were White and middle class. Families received a photograph magnet and tote bag as souvenirs of participation. We tested hand dominance as in Experiment 1. Three children were excluded from the final analyses: One child refused to pick up the hammer, one child did not have a clearly dominant hand, and the video file from one participant was lost due to equipment failure.

Apparatus, procedure, and data coding. The procedure was identical to that of Experiment 1 with a few exceptions. Before the trials began, the experimenter told children to put their nondominant hand in an oven mitt and told them to use only their dominant hand. Then we compared children's selection of the end-state comfort grip or an ulnar grip with only their dominant hand available on 10 easy and 10 difficult trials, blocked and randomized as in Experiment 1. After the 20 trials of hammering with only a dominant hand, the experimenter removed the oven mitt and asked children to hammer with their nondominant hand for five

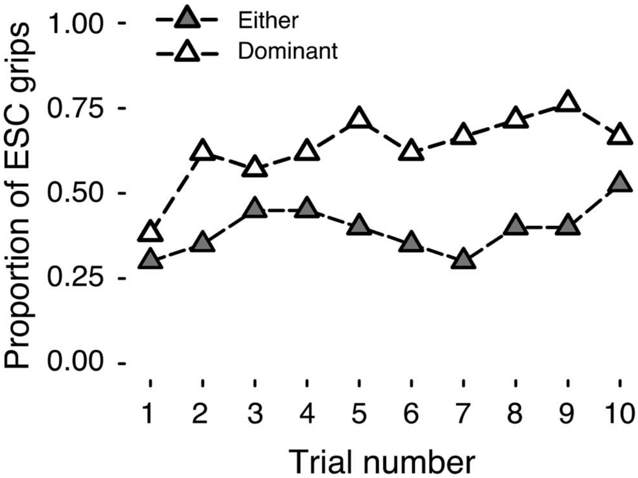

Figure 4. Proportion of end-state comfort (ESC) grips at each difficult trial for Experiment 1 (filled symbols) and Experiment 2 (open symbols). The 10 difficult trials were randomly interspersed with 10 easy trials across the session. Logistic regression showed no trend across trials in Experiment 1 but an increase in ESC grips in Experiment 2.

trials and with an ulnar grip using their dominant hand for five trials. To obtain equivalent trials of the three hammering methods, we instructed children in how to engage with each method. For the ulnar trials, the experimenter placed children's hand in the appropriate position on the hammer handle.

To assess planning and implementation, coders scored children's behaviors as in Experiment 1 with one exception: To obtain a more sensitive measure of hammering efficiency, coders scored the number of times children *missed the peg* during each trial, rather than if the child missed the peg at least once in a trial.

A primary coder scored 100% of the data, and a secondary coder scored 25% of each participant's trials to ensure interrater reliability. Coders agreed on 98%–100% of instances for each categorical variable (κs = .95–1.00); the correlation coefficients for number of strikes and number of misses per trial were $r(97)$ = .99 and

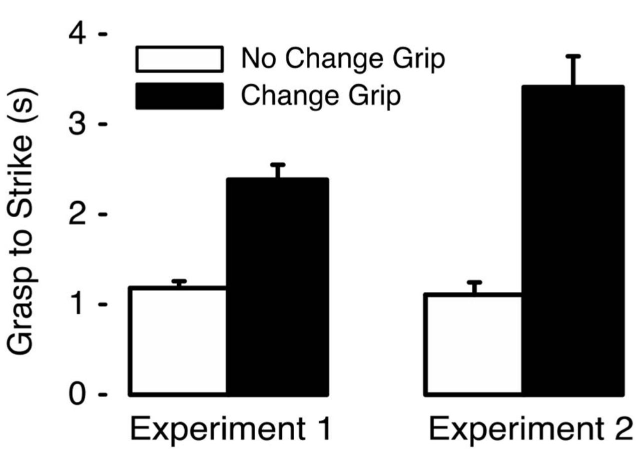

Figure 5. Duration of time between initial grip and first contact with the peg while maintaining the initial grip strategy (white bars) and changing the initial grip (black bars). Error bars denote standard error.

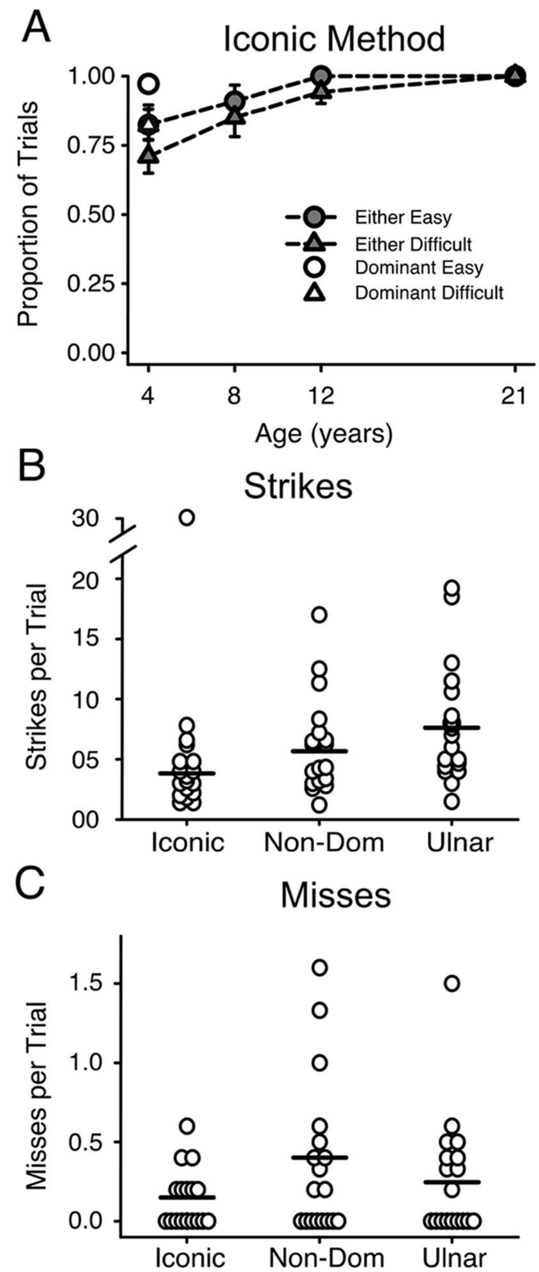

Figure 6. Implementation methods and efficiency measures. Error bars denote standard error. Panel A: Average proportion of trials by age and condition for sole use of the iconic method while implementing the hammer during a trial. Data from Experiment 1 (in which participants could use either hand) are represented with filled symbols; data from Experiment 2 (in which children could use only their dominant hand) are represented with open symbols. Note that Experiment 1 included four age groups (4-, 8-, and 12-year-old children and adults) and Experiment 2 included only 4-year-olds. Circles denote easy trials (handle pointed toward the dominant hand), and triangles represent difficult trials (handle pointed toward the nondominant hand). Panel B: Number of strikes required to flatten the peg using various hammering methods in Experiment 2. Panel C: Number of misses per trial using various hammering methods in Experiment 2. Symbols represent averages for individual children. The group means are denoted by the horizontal lines. Non-Dom = nondominant.

$r(97) = .79$, respectively. Disagreements between coders were resolved through discussion.

Results and Discussion

As in Experiment 1, we recoded handle direction from right or left to easy or difficult. We used a series of repeated-measures ANOVAs (e.g., easy or difficult conditions) on each outcome measure. We also employed 2 (experiment: 1 or 2) × 2 (condition: easy or difficult) mixed-design ANOVAs to assess how limiting hand choice affected children's planning. Preliminary analyses showed no effect of trial block or gender, so these factors were excluded from further analyses. Again, all analyses used the standard alpha value of .05.

End-state comfort. As in Experiment 1, 4-year-olds showed end-state comfort on nearly every easy trial (see the open circle in Figure 2A). But they showed end-state comfort on $M = 62\%$ of difficult trials (see the open triangle in Figure 2A), $F(1, 20) = 16.98$, $p = .001$, $\eta_p^2 = .46$. Children's use of end-state comfort was higher than in Experiment 1 (compare the open and filled symbols in Figure 2A). The ANOVA (see Table 2, top row) confirmed a main effect of experiment and condition.

Because children could not use their nondominant hand on difficult trials, when they failed to use an end-state comfort grip, they used the awkward ulnar grip—thumb away from the hammerhead (see the open symbols in Figure 2C). The ANOVA confirmed more initial ulnar grips on difficult than easy trials, $F(1, 20) = 16.98$, $p = .001$, $\eta_p^2 = .46$. Ulnar grips did not increase relative to Experiment 1; as shown in Figure 2C, the two triangles are nearly overlaid and the ANOVA revealed only an effect of condition (see Table 2, row 2).

Although we eliminated use of their nondominant hand, children were resourceful and managed to correct an initial ulnar grip by using their body (torso or lap) or the table to stabilize the hammer while they moved their hand to a radial grip. The process was cumbersome—it took more than 2 s longer to strike the peg when children changed their initial grip than when they did not (see the right panel of Figure 5), $t(11) = 7.45$, $p < .001$, $\eta_p^2 = .85$. As in Experiment 1, changing grips was limited solely to difficult trials, $F(1, 20) = 9.78$, $p = .005$, $\eta_p^2 = .33$ (see the open symbols in Figure 2D), and as expected, changes were always (100%) in the direction of changing ulnar to radial grips, now that the possibility of two-handed grips was eliminated.

Table 2
ANOVA Main Effects and Interactions Comparing Participants in Experiments 1 (Hammering With Either Hand) and 2 (Hammering With Dominant Hand Only)

Variable	Experiment effect		Condition effect		Interaction	
	F	η_p^2	F	η_p^2	F	η_p^2
End-state comfort grip	4.20*	.10	54.49***	.58	2.35	.06
Ulnar grip	.19	.01	33.31***	.46	.20	.01
Change in grip	5.23*	.12	35.09***	.47	3.47	.08
Iconic method	4.36*	.10	10.25**	.21	.16	.00

Note. ANOVA = analysis of variance.
* $p \leq .05$. ** $p < .01$. *** $p \leq .001$.

Changing grips decreased dramatically from Experiment 1 to Experiment 2 (compare the filled and open triangles in Figure 2D). The ANOVA confirmed a main effect of experiment and condition (see Table 2, row 3). It is important to note that the decrease in changing grips does not necessarily mean that the greater time lost discouraged children from changing their grip. More grip changes in Experiment 1 may instead reflect swapping the hammer from the nondominant hand to the dominant hand. We performed a follow-up analysis, looking at only those trials in Experiment 1 where 4-year-olds initially grasped the hammer with an ulnar grip in the dominant hand to make the data more comparable to the data in Experiment 2. Four-year-olds changed their initial ulnar grip more frequently in Experiment 1 ($M = 86.8\%$, $SD = 22.2\%$) than in Experiment 2 ($M = 55.8\%$, $SD = 47.3\%$). A one-way ANOVA confirmed a main effect of experiment, $F(1, 26) = 4.40$, $p = .046$. Therefore, we conclude that children did view changing their initial grip as a substantial cost when they were not permitted to use their nondominant hand.

Eliminating grips with the nondominant hand decreased the total number of possible grips, but children still displayed considerable inter- and intraindividual variability on difficult trials (see Figure 3D). The majority of children (62%) used at least two types of initial grips, providing further evidence of a transitional period. Ten children, almost 50% of the group, used the end-state grip either exclusively or on all but one trial. Their data look much like the data of the majority of 8-year-olds. Six children had the end-state comfort grip in their repertoire, but it had not become a consistent response. These children may have been fully aware of the costs incurred by an ulnar grip but vacillated between it and the end-state comfort grip because both exerted noticeable strength. Finally, five children always picked up the tool in an ulnar grip on difficult trials. Of these, three continued to hammer with an uncorrected ulnar grip on virtually every trial, and two corrected their grip on every trial.

The increased penalty for changing their grip may have led to learning over trials not evidenced in Experiment 1. Indeed, 4-year-olds showed a reliable increase in end-state comfort grips on difficult trials as the session progressed (see the open triangles in Figure 4). A logistic regression predicting end-state comfort from trial number confirmed that 4-year-olds were more likely to show end-state comfort on later than earlier difficult trials ($\beta = .13$), Wald's $\chi^2(1) = 5.32$, $p = .021$. Presumably, they wanted to hammer with the iconic method, and because it was more difficult to change their initial grip, children chose more end-state comfort grips as trials progressed.

Implementing the hammer. As in Experiment 1, 4-year-olds predominantly used the iconic hammering method ($M = 90.1\%$ of trials), and they did so more frequently on easy than difficult trials (see the open symbols in Figure 6A), $F(1, 20) = 5.14$, $p = .035$, $\eta_p^2 = .21$. Children were more likely to use the iconic method in Experiment 2 than in Experiment 1 for both easy and difficult conditions (compare the filled and open symbols in Figure 6A). The ANOVA confirmed a main effect of experiment and condition (see Table 2, bottom row). Higher levels of the iconic method in Experiment 2 compared with Experiment 1 are likely due to eliminating the possibility of using the nondominant hand and bimanual strategies.

To determine whether hammering method influenced children's accuracy, we compared the first five trials that a participant hammered with an iconic grip (radial grip with the dominant hand), an ulnar grip in the dominant hand, and a radial grip in the nondominant hand. An unexpected, curious finding emerged. When the experimenter handed children the hammer with the handle pointing toward their nondominant hand for the ulnar grip trials, 19 of 21 children tried to grasp the handle with an underhand end-state comfort grip. To get them to implement the ulnar grip, the experimenter had to take their hand and place it in the appropriate position on the handle. All five of the children who failed to show end-state comfort on difficult trials reached with an underhand radial grip when the experimenter handed them the hammer on ulnar trials.

In contrast to the findings in Experiment 1, implementing the hammer with an ulnar grip incurred some cost (see Figure 6B and 6C). Children required more strikes to pound the peg flat when using an ulnar grip ($M = 7.86$, $SD = 5.01$) compared to the iconic method ($M = 5.14$, $SD = 6.51$) or with their nondominant hand ($M = 6.16$, $SD = 4.03$). Although the ANOVA revealed only a marginal difference between hammering methods, $F(2, 34) = 2.61$, $p = .088$, $\eta_p^2 = .13$, the differences were dampened due to one child averaging 30.2 strikes per trial when using the iconic method (she performed 20–45 tiny soft strikes across the five trials; see Figure 6B). With the outlier excluded, the ANOVA revealed a significant effect of hammering method $F(2, 32) = 11.30$, $p < .001$, $\eta_p^2 = .41$. Post hoc analyses showed that children required more strikes to pound the peg flat when using an ulnar grip ($M = 7.65$, $SD = 5.08$) compared with their nondominant hand ($M = 5.52$, $SD = 3.08$; $p = .036$). Additionally, both the ulnar and nondominant hammering methods required more strikes than with the iconic method ($M = 3.67$, $SD = 1.87$; $ps = .001$ and .005, respectively). However, Figure 6B shows that children's data for strikes is highly skewed. For comparison, we ran a nonparametric Friedman's test, which is more suitable for a nonnormal distribution. Even when including the outlier, this test agreed there were significant differences between hammering methods; $\chi^2(2) = 10.03$, $p = .007$.

Children were also more likely to miss the peg when using the nondominant hand. The ANOVA confirmed a main effect of hammering method $F(2, 34) = 4.15$, $p = .024$, $\eta_p^2 = .20$. Post hoc analyses revealed that children missed the peg more frequently with the nondominant hand ($M = .36$ misses per trial, $SD = .49$) than with an ulnar grip ($M = .26$ misses per trial, $SD = .38$) or the iconic hammering method ($M = .13$ misses per trial, $SD = .18$; $ps = .017$ and .060, respectively). Again we ran a nonparametric Friedman's test, because Figure 6C shows the distribution for misses is also skewed. This test was marginally significant, $\chi^2(2) = 5.63$, $p = .060$. Because the variable number of strike attempts could affect the number of misses, we also calculated a miss rate by dividing the number of misses by the number of strike attempts on each trial for each method. The ANOVA was marginally significant $F(2, 34) = 2.98$, $p = .06$, $\eta_p^2 = .15$. Once more, 4-year-olds missed the peg more per strike when using their nondominant hand ($M = 6.6\%$ of strikes, $SD = 8.2\%$) than when using an ulnar grip ($M = 3.7\%$ of strikes, $SD = 4.3\%$) or the iconic method ($M = 3.9\%$ of strikes, $SD = 5.2\%$; $ps = .058$ and .070, respectively).

Summary of Experiment 2. The increased use of end-state comfort grips in Experiment 2 indicates that some 4-year-olds were becoming aware that an ulnar grip is less efficient than a radial grip and incurs lost time when changing from an ulnar to a radial grip. This awareness may have driven them toward exclusive use of the end-state comfort grip, as shown by increased choice of this grip over trials. Figure 3D represents children in every state of this transition—some already using only end-state comfort grips and others clinging to the ulnar grip to varying degrees. The fact that the five children who failed to demonstrate end-state comfort on any difficult trials yet tried to reach with an underhand radial grip when the experimenter offered the hammer on ulnar trials suggests that the underhand grip was in their repertoire. We discuss this further in the next section.

General Discussion

The purpose of the current research was to replicate the developmental trend in planning for end-state comfort with a new hammering task and to intensively examine the development of end-state motor planning at its beginning in preschoolers. More than a dozen articles have shown that preschoolers perform worse than older children and adults in a variety of end-state comfort tasks—flipping dowels, cups, and pencils; turning handles; inserting swords into holes; and stepping to avoid a barrier (for reviews, see Adolph & Robinson, 2015; Wunsch et al., 2013). The end-state comfort grip can be seen in preschool children as young as 3 years of age, with a growth spurt between 5 and 8 years, and it reaches adult levels at about 12 years of age. Our hammering task confirms the general findings from previous work. The 8-year-olds (76% end-state comfort) and 12-year-olds (91%) replicated the age effect found in school-age children. For 4-year-olds, the percentage of end-state comfort grips in Experiment 1 was 38%, the same percentage as for the bar transport task used by Knudsen et al. (2012), and close to the 45% found by Weigelt and Schack (2010) in their dowel task. In Experiment 2, in which children were confined to using their dominant hand, we found that the percentage of end-state comfort grips was 62%, which is comparable to data from 4-year-olds in bar transport tasks (71% reported by Hughes, 1996, and 60% by Smyth & Mason, 1997) and the overturned glass task (69% by Knudsen et al., 2012). Because task procedures, number of action steps, and sample size affect end-state comfort (Wunsch et al., 2013), we consider the data from both of the current experiments to fall within the range reported in the literature.

Unique Features of the Hammering Task

Our hammering task had several features that differed from those of previous work in important ways. First, our task was familiar and highly motivating, and the goal of hammering the peg was self-evident; these features allowed us to collect many more trials (20) per child than was done in most previous work. As a consequence, we could obtain robust measures of intraindividual variability. An important contribution of both studies was to reveal high intraindividual variability in initial grips—the majority of 4-year-olds demonstrated end-state comfort on at least one trial but displayed various awkward initial grips on other trials. Because most previous research did not examine individual data, it is likely that reporting only group means obscured the prevalence of end-state comfort on a subset of trials in preschoolers. Second, nearly all previous work with preschoolers has focused solely on children's initial grip (an important exception is Wunsch, Weiss, Schack, and Weigelt, 2015), who reported changes in grip). In addition to initial grip, our task permitted analyses of error corrections and measurement of efficiency. Given the nature of hammering, we could compare children's initial grip as they reached out to grasp the hammer with their grip while using the hammer to pound the peg. We found that preschoolers, like older children and adults, preferred to hammer with the iconic, overhand, radial grip, but this frequently required correcting the initial grip. When children persisted in hammering with an ulnar grip, more strikes were required, and changing the initial grip cost time. Our procedures allowed us to test whether preschoolers took note and avoided such inefficiency and suggested ways this could propel end-state-comfort grips to their eventual dominance. Finally, in contrast to most previous studies, which required children to use only their dominant hand, we compared children's performance when they were allowed to use either hand to their performance when only their dominant hand was available. Thus, we could investigate whether allowing children the use of both hands affected their use of end-state comfort grips (it did—end-state grips increased when constrained to their dominant hand), whether children would spontaneously use their nondominant hand on difficult trials (frequently they did), and whether children implemented the hammer more efficiently with their dominant hand (they did in Experiment 2). These unique features of the hammering task provide new insights into the *reasons* for young children's variable strategies.

The Value of Variability

What does the variability in grip strategies say about how children acquire the end-state comfort grip? Perhaps most important, intraindividual variability reveals how children choose from among various motor strategies to achieve a goal. Success on the end-state comfort task requires children to envision the correct initial grip on the tool and also the goal action. High variability in the 4-year-olds was shown in the initial grip but not in their implementation of the tool. Children predominantly used the adult-like iconic hammering method (illustrated in the right side of Figure 1G) in both experiments. Indeed, children's preference for the iconic method was so strong that when they initially grasped the hammer in a manner inconsistent with end-state comfort (the ulnar grip illustrated in Figure 1H or a radial grip with the nondominant hand), they frequently changed their grip to implement the hammer with the iconic radial grip in the dominant hand. The change in grips was virtually always from a non-iconic to an iconic grip in both experiments. This directional shift strongly suggests that children knew what the best grip for hammering would be but had trouble planning the initial grip that would result in the correct final position for implementation. Experiment 2 provided evidence that children can learn within a single session to avoid the ulnar grip when it is shown to be more costly.

The intraindividual variability of the 4-year-olds is an excellent example of Siegler's (1996, pp. 86–90) notion of overlapping waves in cognitive change. Rather than viewing development as progressing in steplike functions with sudden changes from less efficient to more efficient behaviors, the "overlapping wave" model describes children as simultaneously representing multiple ways of solving a problem. For example, as 5- to 7-year-olds master addition, they display five different addition strategies and the majority of children use at least three strategies across trials (Siegler, 1987). Siegler pointed out that having a variety of strategies enhances learning in the long term but may hurt performance initially. Cognitive change occurs when frequencies of alternative behaviors shift. In looking at Figure 3, clearly the majority of 4-year-olds entertained alternative, competing grips in the end-state comfort task. Siegler (1989, 1994) stressed that variability is a necessary aspect of learning better strategies. Furthermore, variability should not be viewed as random, because each strategy represents some means of solving the problem, although some are superior to others. Four-year-olds seemed to realize this; we never saw a child pick up the hammer in an end-state comfort grip then change out of it before hammering. Siegler (1996) predicted that variability would be greatest during early learning and would decrease as expertise increased this is the age trend we found in children's acquisition of the end-state comfort grip.

The specific grips that children use are also affected by the particular tool and how it will be implemented. For example, picking up a spoon and eating food from it invites different grips compared with wielding a hammer to pound a peg. With the spoon handle pointing away from their dominant hand, 4-year-olds frequently choose their nondominant hand in a radial grip, along with occasional use of the underhand grip and ulnar grip with the dominant hand (Keen et al., 2014). In addition, some 4-year-olds use a "fingertip grip" and 8-year-olds use it to a greater extent. Using a spoon is a precise and more delicate affair, in contrast to the case with a hammer, which requires a power grip with the whole hand. The fingertip grip is a precision grip, requiring control over individual fingers. A minority of 4-year-olds have discovered this grip, and it will be years before it dominates their spoon postures. Like the current work, spoon use confirms that 4-year-olds are in a transitional state where different hand postures compete in tool use.

When children lack a stable representation for the most efficient action, they exist in a state of transition such that several action paths lead toward the final goal and none stand out as superior. An analogy is when one moves to a new city and knows several different routes to get to work. Initially, none seem superior and various routes are tried. The shortest route in mileage may not be the most efficient if it entails more stoplights and slower traffic. Eventually one decides which is the most efficient route on the basis of traffic patterns, time of day traveling, and so on. So it is with preschoolers grappling with the end-state comfort task. Initially, children try many different grips because the representation of the most efficient grip must be worked out through practice. Finally, children consistently choose the underhand grip with the dominant hand because no change in grip or hands is necessary to complete the action efficiently. The most striking aspect of the developmental data is that this process takes years for children to adopt the end-state comfort grip as the most efficient.

Incorporation of New Strategies

After new strategies are discovered, how do they become integrated into children's repertoire and compete with existing strategies? Siegler and Jenkins (1989) proposed that motivation to try a new strategy can arise from realizing that the old strategies do not work well in a new situation. Each time a new strategy is used correctly, it gains strength. In time, it will replace the previous more habitual strategy if it proves to be more efficient. Thus, the acquisition of new strategies changes the frequency of already existing strategies. If old competing strategies are strong, it may take a long time for children to deem a new strategy more effective. In end-state comfort studies, the overhand grip on the handle of a tool or on a bar in the bar transport task, is overlearned. Infants' typical pickup of a toy is the overhand grip, and this continues to be the favored grip throughout toddlerhood (McCarty et al., 2001). Stöckel et al. (2012) described two competing systems in play in the end-state comfort task. The "habitual system" selects the often-used overhand grip, and children must inhibit this strong habit. The "goal-directed system" takes into account future requirements, and if allowed, the person will select the underhand grip. Stöckel and Hughes (2015) showed that when additional precision constraints to the initial grasp were added, 6- to 10-year-olds display reduced levels of the underhand grip indicating that greater cognitive costs interfered with planning and increased the competition between the habitual and goal-directed systems. Indeed, tests of children's cognitive ability—inhibition with an Animal Stroop task and planning with the Tower of London puzzle—were positively correlated with performance on an end-state comfort task (Stöckel & Hughes, 2016). Although Stöckel and Hughes (2015) used different language to describe how children choose from among grips, their analysis agrees with Siegler's (1996) model in postulating that competing strategies with various levels of strength lead to greater instability in behavior. Several researchers have proposed competing processes to explain how behavior changes over time. Herbort and Butz (2011) studied how end-state-comfort selection in adults was subject to both the habitual system and a goal-directed system. Marcovitch and Zelazo (2009) proposed a two-component process in which habit strength competes with a conscious representational system to explain infants' success or failure on hidden object tasks. Like Stöckel and Hughes (2015) and Siegler (1996), Marcovitch and Zelazo (2009) predicted a period of instability when behavior is variable before the more mature cognitive process wins out. High variability may well be a necessary stage in the learning process for children because choosing from among competing responses generally results in divergent behaviors. After the correct response, or the most efficient grip in the case of the hammer, becomes dominant, other responses drop out and behavior becomes homogeneous.

Perhaps the children who did not produce an underhand grip in Experiments 1 and 2 did not yet have the underhand grip in their repertoire. This explanation has been posited for the complete lack of underhand grips in studies examining infants' use of spoons (Keen et al., 2014). However, this explanation is unlikely, given our unexpected observation in Experiment 2. At the end of the study, to test the effectiveness of multiple hammering methods, the experimenter handed the hammer to the child. For the ulnar implementation trials, the experimenter held the hammer by its head and presented the handle facing away from children's dominant hand. Therefore, an overhand reach with the dominant hand would lead to an ulnar grip. Nearly every child initially reached for the hammer with an underhand grip, using the dominant hand—including the five children who never showed end-state comfort. When this happened, the experimenter corrected the child's grip to ulnar and frequently had to do so again on the next trial. The underhand grip was in children's repertoire; they simply failed to use it during the difficult trials.

How Does Efficiency Work to Advance One Strategy Over Another?

Efficiency advances in stages. First, one strategy must actually be more efficient. Second, children must recognize its better performance. Finally, children must value that efficiency before a new strategy will gain ascendency over old ones with strong habit strength. Our data showed that an ulnar grip and a nondominant grip were less efficient than was a radial grip in the dominant hand because pounding the peg flat required more strikes and incurred more misses. Despite this obvious superiority, some 8-year-olds and one 12-year-old tried pounding with the nondominant hand for a few trials (see Figure 3B and 3C). In Experiment 2, changing the ulnar grip was more costly in time than in Experiment 1, whereas not changing the grip remained less efficient. In response to this change in procedure, children were more likely to use the underhand end-state comfort grip and were less likely to change grips compared with the case in Experiment 1. Having fewer but more costly options helped 4-year-olds to select the initially uncomfortable grip that would turn into the comfortable final grip. An increase in end-state comfort grips as trials progressed indicated that children responded to the superior efficiency within this single session. The third issue is more difficult to evaluate—when do children recognize and also value the end-state comfort grip's efficiency enough to raise it above all other competing responses? By 4 years of age, a few children had reached this level and selected the end-state comfort grip on every trial. Within individual children, the state of overlapping and competing behaviors will probably persist as long as they are about equal in efficiency. As the underhand radial grip becomes noticeably more efficient or the cost of other grips becomes apparent, the alternate grips will drop out. In the case of end-state comfort, this process could last for months or even years, and it will vary with the task and cognitive constraints imposed.

Conclusions

During early learning, children entertain multiple means to solve a problem, resulting in inconsistent behaviors. The analysis of variability within and between individuals in both Experiments 1 and 2 verify this inconsistency. At the point where old and new behaviors are about equally efficient, they compete, producing an unstable flow of behavior. Initially a new behavior is less favored than the old behavior, but through practice the new behavior achieves a higher efficiency, and the old behavior drops out. To become truly proficient in a skill, one must give up old patterns of behavior that served well initially and adopt new ones that allow a higher level of skill to be reached. Such a process holds for locomotion as infants progress from proficient crawlers to stumbling walkers, then finally to proficient walkers (Adolph & Tamis-LeMonda, 2014). A similar process appears to be operating with end-state comfort. Longitudinal studies of children between 4 and 8 years of age could reveal whether increased efficiency in pounding with the radial grip parallels their routine adoption of the underhand grip in the end-state comfort task.

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