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PAPER

The sources of skill in seriating cups in children, monkeys and apes

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Abstract

Is a concept of either reversibility or of hierarchical forms of combination necessary for skilled seriation? We examined this question by presenting seriating cups to adult capuchin monkeys and chimpanzees and to 11-, 16- and 21-month-old children. Capuchins and chimpanzees consistently created seriated sets with five cups, and placed a sixth cup into a previously seriated set. Children of all three ages created seriated five-cup sets less consistently than the capuchins and chimpanzees, and were rarely able to place a sixth cup into a seriated set. Twenty-one-month-olds produced more structures containing three or more cups than did the younger age groups, and these children also achieved seriated sets more frequently. Within all participant groups, success at seriating five cups was associated with the frequency of combining three or more cups, regardless of form. The ability to integrate multiple elements in persistent combinatorial activity is sufficient for the emergence of seriation in young children, monkeys and apes. Reliance on particular methods of combination and a concept of reversibility are later refinements that can enhance skilled seriation.

Young children through the preschool years are typically attracted to sets of objects that present ordered relationships of size or volume, and they will work spontaneously to create structures that make use of, or express, the ordered relationships present in the collection (e.g. Inhelder & Piaget, 1969; Sinclair, Stambak, Lezine, Rayna & Verba, 1989). For example, children are likely to stack blocks from largest to smallest, or to nest cups of different sizes. Children's efforts to nest cups move from initial limited actions (pairing two objects) through ineffective sequences that result in structures of varying sizes and compositions, to well-ordered and effective action sequences that consistently produce seriated sets (Greenfield, Nelson & Saltzmann, 1972; Woodward, 1972). Once the child can seriate a set of cups effectively, that child can subsequently insert additional cups in the correct position in the seriated set. This achievement marks skilled seriation of cups. Skill encompasses both the creation of a seriated set, and the expansion of a seriated set.

The development of skill in this simple seriation task poses many interesting questions for developmental scientists. Most investigators looking at activity with nesting cups have approached this task from the perspective of hypothesized cognitive elements embodied in the successive acts of combining cups. For example, Greenfield *et al.* (1972) found that children who are successful at seriating five cups, and at placing a sixth cup into a seriated set, rely more on a method of combining cups that the authors labeled 'subassembly' than they do on the two other possible methods of combining the cups (see Figure 1). The simplest method, and one that can never result in a seriated set if used exclusively, is called 'pairing'. Pairing involves putting one cup together with one other cup. Subassembly involves placing one cup into another (or a set of others), then moving the multi-cup unit as one element into a third cup.

Along with placing one cup into a set of others (called 'potting'), subassembly results in the creation of multi-cup structures. The difference between potting and

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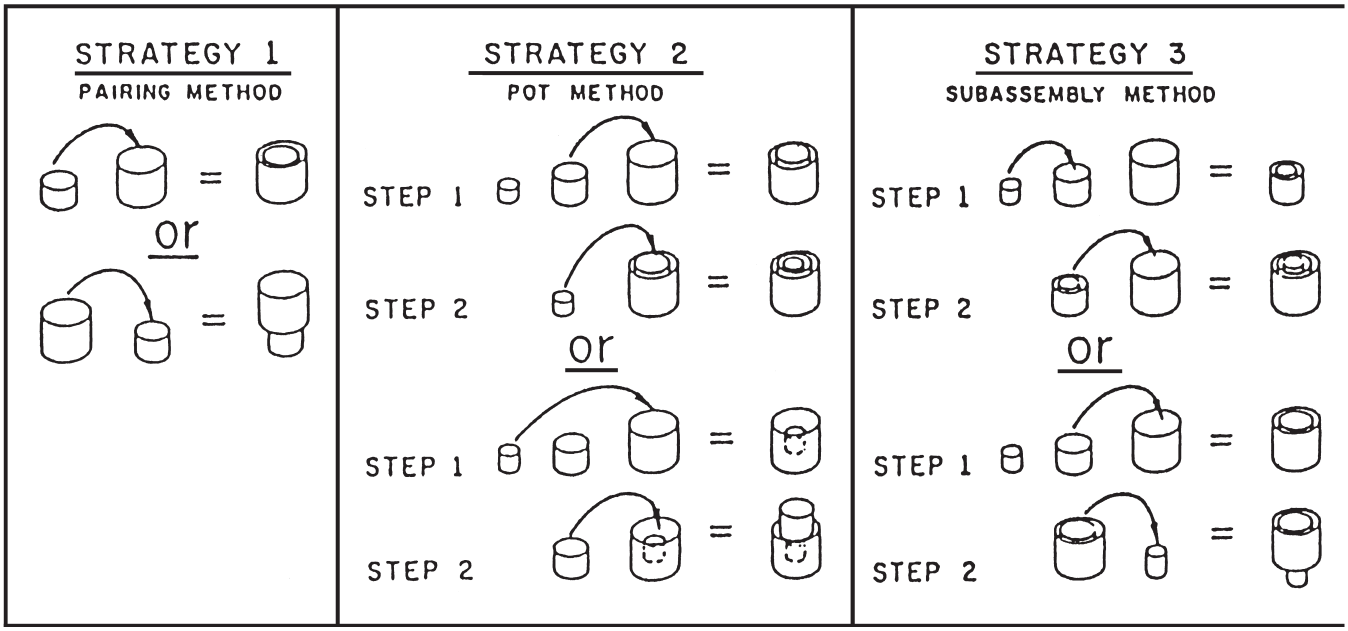

Figure 1 *Strategies of combining nesting cups as identified by Greenfield* et al. *(1972).*

subassembly is that the former involves a single actor and multiple recipients; the latter involves multiple actors and a single or multiple recipient(s). In Greenfield's (1991) terminology, subassembly results in the hierarchical combination (two or more lower-level units combined into one new unit) of multiple cups; pairing and potting do not. In cross-sectional sampling, Greenfield *et al.* (1972) observed a developmental progression with age in the reliance on different patterns of combining cups, from pairing to potting to subassembly, and an increase in success at seriation with the increasing use of subassembly (see also Sugarman, 1983). DeLoache, Sugarman and Brown (1985) also report, in another cross-sectional study, that children 18 months to 42 months showed decreasing reliance on potting and increasing use of subassembly. Success at seriation also increased with age, as in Greenfield *et al.*'s (1972) and Sugarman's (1983) studies.

Greenfield *et al.* (1972) and Greenfield (1991) argue that subassembly, because it involves hierarchical combination, illustrates a more sophisticated approach to the problem of arranging multiple objects than does potting. Greenfield and colleagues attribute the older children's increasing success at seriation to increasing reliance on a subassembly strategy for combining the cups. Further, Greenfield *et al.* (1972) and DeLoache *et al.* (1985) suggest that the development of skill at seriating cups, and particularly success at placing a middle cup into an existing seriated set, reflects the child's growing recognition that one cup can simultaneously be larger than a specific other cup, and smaller than a different other cup. In other words, middle cups must be placed in a certain order to fit correctly. The ability to fit the cups together consistently is taken as evidence that the behavior is conceptually mediated; and in this view, that the child recognizes (at the level of action) the property of reversibility in the cups (because such recognition is necessary for success at the task). The word 'strategy' to describe recurrent patterns of actions with the cups reflects this conceptual interpretation of the nature of skill in seriation (Greenfield *et al.*, 1972).

As initially proposed by Inhelder and Piaget (1969), mastery in performance (skill) in seriation tasks is taken as evidence that the performer uses a concept of reversibility to organize action. Reversibility refers to the premise that what can be done (or composed) can be undone (or decomposed). With respect to logical cognition, this sense of reversibility entails recognition that different whole units can be combined to form a new, inclusive whole, but that this whole can potentially be broken down, or the additive operation reversed, to reinstate the smaller wholes. With respect to seriation, reversibility implies an understanding that a single cup can simultaneously be smaller than one cup and larger than another cup and that its role changes (reverses) depending on which relation is being considered.

In this study, we examine seriation in very young children (11 to 21 months-old), when seriation skill is emerging. Previous studies (Greenfield *et al.*, 1972; DeLoache *et al.*, 1985) have shown that children between 11 and 20 months are not often successful at seriating five cups, and children in this age range who do manage this task usually cannot manage to insert a middle cup into an already-seriated set. Greenfield *et al.*'s (1972) analyses emphasized age differences in one aspect of action (the children's reliance on particular patterns of combination, and most especially, subassembly). Sugarman (1983) assessed the organization of activity with nesting cups in terms of 'local', or move-by-move, planning. DeLoache *et al.* (1985) expanded the focus of their study to include how children managed errors committed during pursuit of seriation. The current study extends the previous works by attending particularly to combinatorial activity in very young children, and by broadening the theoretical consideration of the initial bases of seriation skill. Children from 1 to nearly 2 years of age master combinatorial manipulation in many situations (e.g. using a spoon and other simple tools; Connolly & Dalgleish, 1989; Brown, 1990; Johnson-Pynn, 1999) and exhibit spontaneous combinatorial manipulation in playful situations (Fenson, Kagan, Kearsley & Zelazo, 1976; Sinclair *et al.*, 1989; Langer, 1986). Thus we expected to see mastery of some components of seriation within this age range. For example, we anticipated that older children, compared to younger children, would combine the cups in increasingly more complicated relational ways, even if they were not particularly successful at seriation.

Case's (1992; Case & Okamoto, 1996) neo-Piagetian theoretical framework offers a more recent theoretical basis from which to consider the development of seriation skill. Case proposes that (1) cognitive activity deploys central conceptual structures, (2) cognitive development involves transformations of these central conceptual structures and thus (3) cognitive development will proceed in a linked, stage-like fashion at least within broad domains of activity. The recurring element of conceptual transformations driving these changes is the nature of the integration of multiple elements into one unit of action. Simultaneous integration of properties is indicative of a more developed conceptual structure than sequential integration because the two properties are handled as one unit rather than successively.

With respect to seriation of cups, Case's (1992) model suggested to us that children's initial combinations of cups will involve sequential actions moving one cup into or onto another (Stage 1.2; typically evident at about 8–12 months in humans, according to Case). The next form (Stage 1.3; typically evident from 12–18 months) involves monitoring the structures arising from sequential actions, and integrating the sequential actions into a coherent system. In this stage, the child will work to create a stable structure with two or more cups, disassembling stacks that are not stable and re-combining cups to achieve stability. Pairing and potting (moving single cups) would characterize activity in both of these stages. At about 20 months (Stage 2.1), the child is able to coordinate two relational structures simultaneously. This achievement should permit more efficient sequential actions with cups, and encourage subassembly. The child's goal at this stage would be to put three or more cups together into a stable structure. Seriation skill could be evident here, although relatively inefficient (where efficiency is measured as the number of moves required to achieve seriation). The next improvement (Stage 2.2; 27–42 months) would appear as expanded attention to two relational units, such as adding cups to the set and (at the same time) dealing with cups that block seriation. Efficiency at seriation could be expected to improve in this stage compared to Stage 2.1. Preschoolers (Stage 2.3; 3–5 years) should be able to focus attention on one working stack, and coordinate a series of actions with this stack to achieve efficient seriation of all the available cups. Furthermore, inserting a middle cup into an existing seriated set of cups should be manageable for children at this stage. Stage 3 (from 5 years), where ordinal skills can be expected, might be evident as consistently perfect or nearly perfect seriation, via any method of combination.

We expected that the 11- to 21-month-old children in our study would be operating at Stages 1.3–2.1 in Case's (1992) scheme: some focusing on a single action at a time (putting one cup together with another), and others working on the relational goal of making a stable structure with multiple cups. We anticipated that children attempting to make multi-cup structures would use all combinatorial methods (pair, potting and subassembly). We were particularly interested in how these children achieved seriation, if they did so, given that either the potting or subassembly method of combining multiple cups is adequate for the purpose. Does the use of subassembly precede seriation, or does attempting to master seriation lead one to use subassembly as an efficient solution to the problem?

Our study also includes a comparative element. We compare the performance of young children with that of monkeys and apes in the same seriation task. We have shown in an earlier study (Johnson-Pynn, Fragaszy, Hirsh, Brakke & Greenfield, 1999) that monkeys and apes can seriate nesting cups with skill, even managing the problem of inserting the middle sixth cup with high rates of success. They did so without a strong reliance on subassembly, although all our participants used subassembly at least occasionally to combine the cups, and proportional use of subassembly was positively associated with seriation of five cups. We compare the data from monkeys and apes (taken from Johnson-Pynn *et al.*, 1999) in this report to examine whether young humans' patterns of action with cups are similar to those seen in other species not known to achieve mature conceptual formulations of seriation (such as reversibility).

Method

Participants

Children

Thirty-six children, 12 each at 11 months (313–355 days), 16 months (465–508 days) and 21 months (617–659 days) of age participated. Each age group had seven to eight males and four to five females. Most children were tested at daycare centers, and the remainder at home. Two to three additional children of each age group began the study but did not complete the full testing sequence; their data were dropped.

Apes

Five chimpanzees (*Pan troglodytes*; 8–25 years, three males and two females) and three bonobos (*Pan paniscus*; 8–14 years, one male and two females) at the Language Research Center, Georgia State University, participated. Six of the eight apes had language training (three were conversationally reared as described in Savage-Rumbaugh, Murphy, Sevcik, Brakke, Williams & Rumbaugh, 1993). All the ape subjects had experience manipulating a variety of objects in the context of interacting with humans in both daily routines and in experimental situations. For example, they had previously learned to operate a joystick to interact with computer displays, they received their meals in bowls and cups and they routinely had a variety of objects as toys. They had not previously been trained to seriate stacking cups, however, nor did they routinely have access to seriated collections of objects. The apes presented a wide range of degree of experience with objects due both to age and rearing environment (e.g. primarily human-reared vs primarily mother-reared). For further details about these apes' early experiences, see Savage-Rumbaugh (1986) and Savage-Rumbaugh, Shanker and Taylor (1998).

Monkeys

Four capuchin monkeys (*Cebus apella*; 5–10 years old, all males) at the University of Georgia participated. Like the ape participants, these monkeys had previously learned to use a joystick to interact with computer displays. They also had some experience with experimental tasks that incorporated manipulating objects, such as using a rod as a tool (Visalberghi, Fragaszy & Savage-Rumbaugh, 1995), although they had less experience of this type than the apes. Moreover, they had less access to varied objects in their daily lives. Overall they were less test-wise than the apes. They had had no previous exposure to seriating objects prior to this work.

Materials

We presented two types of commercially available plastic toy nesting cups differing in size and color to all participants. The set presented to the children and monkeys contained six cups (Kiddie Products, Inc., Avon, MA), each a different color and 1.5 cm (smallest cup) to 2.2 cm (largest cup) in height. The set used with the apes (Shelcore, Inc., Piscataway, New Jersey, USA) consisted of three different colors of cups that measured 1.7 cm (smallest cup) to 4.5 cm (largest cup) in height. We gave the apes, with larger hands, a larger set of cups because we suspected that larger cups would be easier for them to manipulate than the smaller cups.

Procedure

Children

We followed Greenfield *et al.*'s (1972) procedure. The experimenter presented the child with an array of five cups on the floor, demonstrated that they could be seriated using the subassembly strategy, and then disassembled the set back to its original configuration. The experimenter then handed the child one of the cups, the size of which varied from trial to trial, and invited the child to play ('Now you play') with the cups. A trial continued until the child seriated the set, or lost interest in the task. A five-cup trial usually lasted no longer than 3 minutes. Occasionally trials were extended an additional minute to accommodate children's continued effort. Verbal encouragement was given throughout the trial but was not contingent upon particular actions with the cups. If the child produced a seriated set of five cups, the experimenter handed him or her a sixth cup that fit into the middle of the previously seriated set, and invited the child to work with the cups again for up to 3 more minutes. Participants completed eight trials. Children typically completed one to three trials per day and completed all eight trials within a two-week period.

Monkeys and apes

Insofar as possible, we used the same manner of testing for the apes and monkeys as for the children. That is, prior to each trial, the participants watched the human experimenter assemble and disassemble the cups into a seriated set using exclusively the subassembly method. Thereafter, the ape participants were offered the cups in the same array as presented to the children, handed one cup, and verbally invited to manipulate the set of cups. They were reinforced with verbal praise and food treats (between trials) for participation and staying on task, but reinforcement was unrelated to the form of activity with the cups. That is, participants were rewarded regardless of efforts or success at seriation. Three of the apes were in an enclosed area with the experimenter; the others were in a test cage with limited tactile access to the experimenter. Apes completed three to four trials per day in accord with their degree of interest in the task. Most of the apes completed six to eight trials. For one ape, we have data for three trials as a result of videotaping difficulty.

For the monkeys, after the experimenter assembled and disassembled the cups, the cups were passed through an aperture to the interior of the monkey's test cage. They were passed through in mixed order of size, following left to right position and front to back row location order as they had appeared on the demonstration tray. As were the apes, monkeys were given verbal encouragement and food treats between trials and at the end of testing. Monkeys generally completed a seriated set or lost interest in the task within the 3 minutes nominally allotted per trial. As with other participants, if at 3 minutes the participant was actively manipulating the cups, we permitted activity to continue for another minute. This happened infrequently (one to three times per monkey), and typically happened when subjects were close to completing the task, as was also the case with the apes and the children. Following completion of the trial, the monkey was removed from the test cage for the day. All monkeys completed eight trials, one trial per day. This testing was administered immediately following test sessions for another task.

Scoring

During video playback, we coded each action combining one cup with another, according to the pairing/potting/subassembly method, and whether seriation was achieved. Although the experimenter demonstrated seriation through nesting the cups, we used the same scoring criteria for other forms of combinatorial activity such as stacking. These data are included in the analyses. Coders practiced with the method to achieve 90% or better agreement for all variables measured on a series of 10 or more trials (selected randomly from the participant pool to represent all ages) prior to collecting data.

We employed two scoring methods. The first method followed Greenfield *et al.* (1972), whereby the strategy used to produce the final structure was coded. A final structure was defined as the largest stack constructed before being dismantled by the participant; one trial could include multiple final structures. We also noted whether final structures were seriated. The second scoring scheme (hereafter called 'all moves scoring') involved coding each successive combination of cups by participants. All moves scoring differed from that used by Greenfield *et al.* (1972) in that we scored each combinatorial act, rather than the single act that produced the final structure. We developed this method to capture our participants' activity in both assembling and dismantling structures during a trial, so that we could examine combinatorial activity more precisely.

Analysis

Parametric tests (ANOVAs, *t* tests) were used to compare groups in all cases where the assumptions of the statistical tests were not violated. Non-parametric tests (Mann-Whitney test, Kruskal-Wallis test) were used when variances across groups were significantly different using Levene's test for homogeneity of variances. According to Keppel (1991), this is the most conservative approach for dealing with data with this structure.

Seriation of five and six cups

We calculated the proportion of trials that ended in a seriated set with five cups. The three age groups of children were compared using a Kruskal-Wallis Chi Square test on arcsine transformed data (following the recommendation of Kleinbaum, Kupper & Muller, 1987, for analysing proportional data). There were insufficient data to conduct a statistical test on sixth cup trials due to children's lack of success in seriating six cups. A Mann-Whitney test was used to compare seriation in 21-month-old children to seriation of monkeys and apes on five-cup trials. We compared children (combining all age groups) to apes and capuchins (combining both genera) on their efficiency in making a seriated five-cup set, defined by the number of moves performed, using a Kruskal-Wallis Chi Square test.

Strategies used to combine cups

For all-moves scoring and Greenfield *et al.*'s (1972) scoring, we used two mixed-design ANOVAs (on arcsine transformed data) to compare the age groups (between participants factor) and strategies (repeated factor) for five-cup trials, and we used Bonferroni post-hoc analyses to compare strategies used by the different age groups with alpha = 0.02. Using a dependent t test, we compared the proportional use of subassembly in five- and six-cup trials with the subset of children ($N = 15$) who succeeded in seriating five cups. Because there were no differences in the proportional use of subassembly between the age groups of children and between the monkeys and apes, we compared all children and nonhuman primates on proportional use of subassembly using two one-way ANOVAs for five-cup and six-cup trials. Detailed findings on combinatorial activity in monkeys and apes are presented in Johnson-Pynn *et al.* (1999).

Data are presented in the text as percentages; standard deviations for percentage values are reported as whole numbers.

Strategies and success at seriation

We compared the proportional use of strategies in children who were successful at seriating five cups ($N = 15$) with those who were not ($N = 21$) using three separate Mann-Whitney tests, one per strategy (pairing, potting, subassembly). Spearman correlations were used to examine the relationship between participants' use of the subassembly strategy and success at seriating five cups, and between the use of the potting strategy and success at seriation.

Frequency of creating complex structures

To determine the frequency with which the participant groups created complex structures, we compared the proportion of structures that contained three or more cups in five-cup trials. Differences among the three age groups of children and monkeys and apes were assessed using an ANOVA and Bonferroni post-hoc tests.

Results

Seriation of five and six cups

Fifteen children (nine 21-month-olds, five 16-month-olds and one 11-month-old) succeeded in seriating all five cups at least once. Children achieved seriation primarily by nesting the cups, although one child produced a seriated tower on occasion, and others sometimes made multi-cup structures that incorporated both nested and stacked elements. Age was associated with significant differences in success at seriation, χ^2 (2) = 9.64, $p < 0.01$. As shown in Figure 2, the 21-month-old age group seriated five cups significantly more frequently (18% of trials, SD = 0.16) than the two younger age groups (16 months: 5%, SD = 0.07; 11 months: 2%, SD = 0.07). Monkeys and apes seriated all five cups on more than half of their trials (53%, SD = 0.40), significantly more often than 21-month-old children (18%, SD = 0.16); Mann-Whitney z (12, 12) = 15.17, $p < 0.001$. Only one ape and one monkey failed to seriate all five cups at least once.

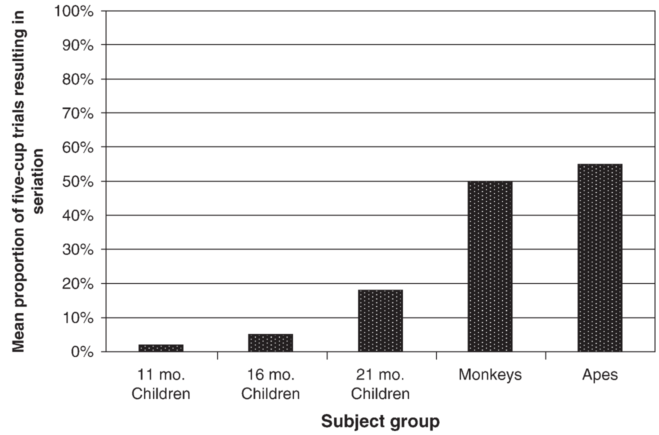

Figure 2 *Proportion of trials that resulted in a seriated structure of five cups.*

Of the 15 children given a sixth cup, two succeeded at placing it correctly into the previously-constructed five-cup set. This occurred only twice out of a total of 23 trials that the 15 children had with six cups (9% success, see Figure 3). Of the seven apes given a sixth cup, four were successful in constructing a six-cup seriated set, and two of the three monkeys successfully seriated six cups. The success rate over all trials with six cups was greater in monkeys and apes compared to children (56%, three monkeys, and 36%, seven apes).

As shown in Figure 4, older children used fewer moves to seriate five cups (16-month-olds: $M = 18.2$; 21-month-olds: $M = 16.9$) compared with the one successful 11-

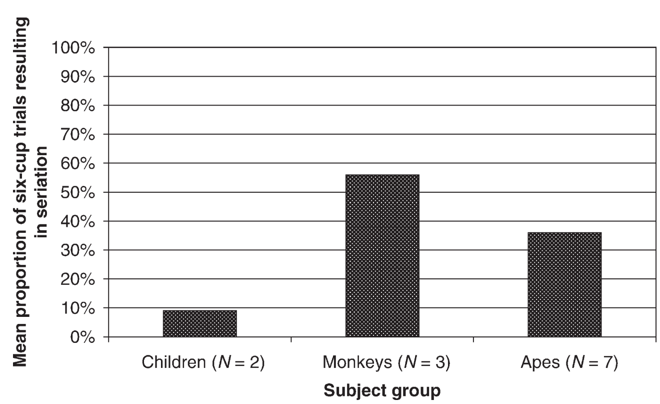

Figure 3 *Proportion of trials in which a sixth cup was correctly placed into an already-seriated set of five cups.*

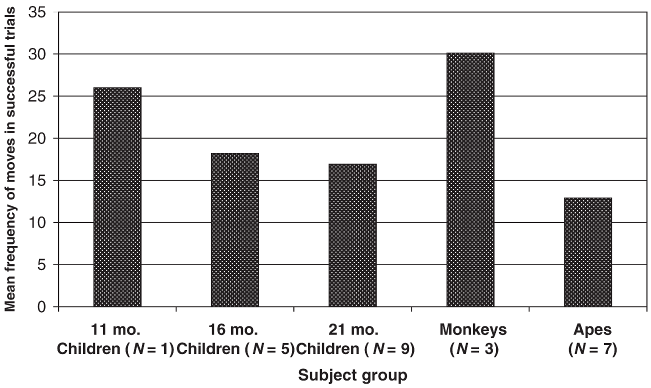

Figure 4 *Average number of moves per trial used to seriate a set of five cups.*

month-old (M = 26). Apes seriated five cups with the fewest number of moves (M = 14.4, SD = 7.8) followed by children (M = 18.1, SD = 7.9) and monkeys (M = 30, SD = 6.1), χ^2 (2) = 6.1, p < 0.05.

Strategies used to combine cups

Children with five cups

According to the all-moves scoring, combinatorial strategies were distributed differently across age groups in trials with five cups, $F(2, 4) = 18.01$, $p < 0.001$, $\eta^2 = 0.52$ (see Table 1). Bonferroni post-hoc tests indicated that pairing was performed more often by 11-month-olds than 16- and 21-month-olds and potting was performed more often by 16- and 21-month-olds than 11-month-olds. The proportion of subassembly did not differ across age groups.

The Greenfield method of scoring activity with the cups produced nearly identical outcomes as the data from all-moves scoring. According to the data derived from the Greenfield method, children differed in the proportional use of the three strategies in trials with five cups, F (2, 4) = 18.22, $p < 0.001$, $\eta^2 = 0.53$. According to Bonferroni comparisons, pairing was performed more often by 11-month-olds than 16- and 21-month-olds and potting was performed more often by 16- and 21-month-olds than 11-month-olds. Use of the subassembly strategy did not differ across age groups. Eleven-month-olds used potting on 83%, pairing on 8% and subassembly on 9% of final structures. The distributions for 16-month-olds were 40%, 45% and 15%, and for 21-month-olds, 26%, 62% and 12%, respectively. These values are very similar to those shown in Table 1, derived from all-moves scoring. Given the similarity in outcome of these scoring methods, hereafter we report only analyses using the all-moves data set.

Table 1 *Distribution of combinatorial strategies in trials with five cups in percentages and (in parentheses) mean frequencies per trial per participant*

	Strategies		
Participant group	Pairing	Potting	Subassembly
11-mo. children (n = 12)	78 (10.35)	10 (1.32)	12 (1.65)
16-mo. children (n = 12)	50 (7.74)	38 (5.94)	12 (1.94)
21-mo. children (n = 12)	38 (5.94)	51 (7.83)	11 (1.66)
Monkeys (n = 4)	33 (11.09)	50 (17.03)	17 (5.84)
Apes (n = 8)	36 (5.63)	38 (5.98)	27 (4.24)

Note. Pairing was performed significantly more often by 11-month-old children compared with 16- and 21-month-old children; 16- and 21-month-olds performed potting significantly more often than 11-month-olds. Subassembly use did not differ across children of different ages. Monkeys and apes used subassembly significantly more frequently than all groups of children.

Table 2 *Distribution of combinatorial strategies in trials with six cups (in percentages)*

	Strategies		
Participant group	Pairing	Potting	Subassembly
11-mo. children (n = 1)	18	27	55
16-mo. children (n = 5)	18	46	35
21-mo. children (n = 9)	27	50	23
Monkeys (n = 3)	9	63	28
Apes (n = 7)	25	40	35

Note. Strategies used by the children in the three age groups were distributed equivalently. Proportional use of subassembly in monkeys, apes and children was also equivalent.

Children with six cups

Strategies used by the children in the three age groups who advanced to trials with six cups did not differ, $F(2, 4) = 1.3$, $p = 0.30$ (see Table 2). Of those children who succeeded at seriation (N = 15 collapsed across age groups), we found that the proportional use of subassembly was greater in six-cup compared to five-cup trials, t (13) = 3.04, $p < 0.01$. The proportional use of subassembly was 16% (SD = 7) in five-cup trials, and 30% (SD = 18) in six-cup trials. Subassembly use of the single successful 11-month-old increased from 33% in five-cup trials to 55% in six-cup trials.

Comparing children to monkeys and apes

As shown in Table 1, children used subassembly proportionately less than monkeys and apes in trials with five cups, $F(1, 46) = 14.04$, $p < 0.0001$. (We pooled data for monkeys and apes for this analysis because the genera did not differ on this measure, as reported in Johnson-Pynn *et al.*, 1999.) Monkeys' and apes' combined use of subassembly was 25% (SD = 16) and that of the children was 10% (SD = 10). In trials with six cups, the 10 nonhuman participants used subassembly on 33% (SD = 16) of their moves compared to 29% (SD = 19) for the 15 children combined (see Table 2). Children's subassembly scores ranged from 0 to 55%; monkeys' and apes' scores ranged from 16 to 65%. The difference between the nonhuman and human groups in the use of subassembly in six-cup trials was not significant, $F(1, 23) = 0.85$, $p = 0.37$.

Relation between the use of combinatorial strategies and the structures created

Children

Children who successfully seriated cups used both potting and subassembly strategies more often than children who never succeeded in seriating five cups, Mann-Whitney z (15, 21) = 2.51, $p < 0.01$ for potting; z (15, 21) = 2.5, $p < 0.01$ for subassembly (see Table 3). The 15 children who seriated five cups at least once used potting to combine the cups for 42% (SD = 14) of their moves and used subassembly in 16% (SD = 10) of their moves. The 21 children who never seriated the five cups used potting in 24% (SD = 22) of their moves and subassembly in 8% (SD = 8) of their moves. The children who were unsuccessful in seriating the cups used the pair strategy significantly more than those children who were successful, z (15, 21) = 3.3, $p < 0.001$. The means for pairing were 69% (SD = 24) for the unsuccessful children and 42% (SD = 18) for the successful children. Recall that a pairing action always preceded a potting or a subassembly action, hence the consistent use of pairing by all participants. Use of subassembly correlated positively with success at seriation, r_s (36) = +0.44, $p = 0.007$. Use of potting also correlated positively with success at seriation, r_s (36) = +0.40, $p = 0.015$.

Monkeys and apes

The differences in performance of those children and those nonhuman participants that did not seriate on any trial cannot be directly compared statistically as only one monkey (of four) and one ape (of eight) were not successful in seriating five cups. However, we can provide descriptive information. Use of the subassembly strategy constituted 9% of moves for both the one monkey and one ape, versus 23% for the 10 successful nonhuman primate participants. These two participants used potting in 45% and 56% of moves, versus 46% for the other 10 participants. As in children, use of subassembly correlated positively with success at seriation, r_s (12) = +0.62, p < 0.03. For monkeys and apes, however, use of potting was negatively, not positively, correlated with success at seriation, r_s (12) = −0.51, $p = 0.09$.

Frequency of creating complex structures

To assess the relation in children between the frequency of combining cups (by any means) and the probability of creating stable complex structures (structures with three or more cups, including towers of stacked cups as well as nested cups), we tallied the frequency of producing three-cup structures in each group. These findings are shown in Figure 5. Ninety-two percent of 11-month-olds' structures were composed of two cups or less. These children composed on average one structure of three or more cups over eight trials, and 11 structures of one or two cups. Over eight trials, the 16-month-olds composed on average 5 structures with three or more cups (43% of

Table 3 *Proportional use (in percentages) of pairing, potting and subassembly by nonhuman primates and children who constructed seriated sets of cups versus children who failed to construct seriated sets*

	Strategies		
Participant group	Pairing	Potting	Subassembly
Children			
Seriators (n = 15)	42	42	15
Non-seriators (n = 21)	69	24	8
Monkeys and apes			
Seriators (n = 10)	33	39	28
Non-seriators (n = 2)	41	51	9

Note. Children who constructed seriated sets were significantly more likely to combine cups using potting and subassembly compared with children who did not construct seriated sets. Non-seriators were significantly more likely to pair cups. Inferential analyses were not possible for the nonhuman primates because of the low number of non-seriators.

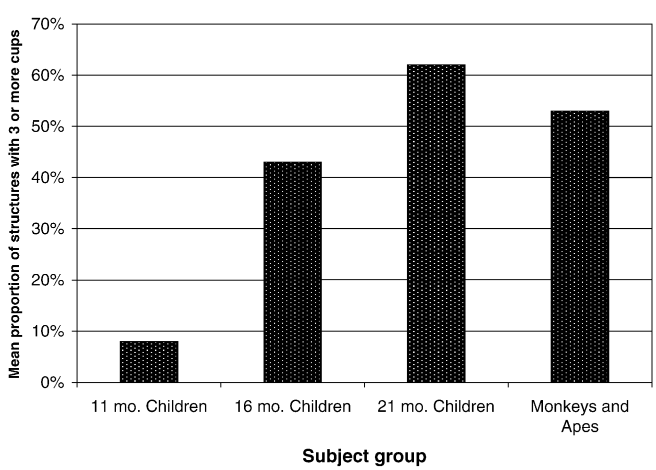

Figure 5 *Proportion of structures constructed with three or more cups.*

total), and 6.6 structures with one or two cups. The corresponding values for the 21-month-olds are 8.5 structures of three cups or more (62% of total) and 6 per trial of one or two cups. ANOVA on arc-sin transformed proportional data indicated that age group affected the number of structures created with three or more cups, $F(2, 33) = 34.23$, $p < 0.0001$, $\eta^2 = 0.67$. Bonferroni post-hoc tests revealed significant differences between 11 and 16 months and 11 and 21 months in the proportion of structures of three cups or more ($p < 0.001$). The two older age groups did not differ significantly from each other in the proportion of structures of three cups or more ($p > 0.02$, where $\alpha = 0.02$ per Bonferroni corrections). Children with a higher proportional use of potting produced a greater proportion of three-cup structures, $r_s(36) = +0.77$, $p < 0.001$. The same relationship was also evident, although weaker, with proportional use of subassembly, $r_s(36) = +0.36$, $p = 0.029$.

Similar analyses with monkeys and apes revealed that monkeys created structures of three or more cups on 46% of trials, and apes on 57% (differences NS) (see Figure 5). Comparing our three age groups of children to the monkeys and apes (pooled), we found that they differed significantly among themselves, $F(3, 47) = 21.58$, $p < 0.0001$. The differences paralleled those found when comparing children among themselves: 11-month-old children differed significantly from all other groups (Bonferroni *t* tests).

Discussion

We set out to determine how very young children managed the task of combining multiple nesting cups to create seriated structures, and to compare their performances to those of nonhuman primates given the same task. We sought to do this because we hypothesized that very young children, although unlikely to be very successful at the seriation task, would nevertheless display a shift with age in the diversity of behaviors expressed, and that the age-related shifts would illuminate the organizational processes the children were using. We were interested in comparing young children's behaviors with other species' behaviors in the same tasks to evaluate theoretical claims about the genesis of complex combinatorial behaviors in humans. To explain the development of combinatorial skill in young children in terms of cognitive processes thought to be unique to humans, one must demonstrate that young children move from an inability to seriate cups to achieve success in some manner that is different than the way that nonhumans manage the same task.

We found that children at 11 months generally failed to create structures with three or more nesting cups, but by 16 and 21 months, such activities were common. Some children between 11 and 21 months of age occasionally managed to seriate five cups, although none of these children did so reliably. Children who seriated five cups were only rarely able to place a sixth cup into the middle of the seriated set they had just constructed. These findings replicate those of Greenfield *et al.* (1972) with children of the same ages. Beyond documenting success, we determined that the means of combining cups to make multi-cup structures changed across age groups. All 11-month-olds paired the cups on more than half of their combinations, and 6 of 12 used pairing on greater than 90% of their actions. Older children used both possible methods of producing multi-cup structures (potting and subassembly) more frequently than did the 11-month-olds. The distribution of combinatorial strategies was more even among the older children; only one child of 24 in the 16- and 21-month-old groups used one strategy on 80% or more of combinatorial actions. In short, the older children were more flexible in their combinatorial activities than were the 11-month-old children. Higher proportions of combinations (achieved by either method of creating structures of three or more cups) were associated with greater success at seriating all five cups.

The children's minimal success at seriating five cups or a sixth middle cup contrasted with the far better success of chimpanzees and capuchin monkeys on these same tasks. Moreover, monkeys and apes succeeded at placing a sixth cup into a seriated set approximately half the time, versus minimal success at this task among the children who seriated five cups. We characterize the monkeys and apes as moderately proficient at seriation, and the children as minimally proficient. Although they differed markedly in success, similarities in other measures of performance were evident between children on the one hand and the nonhuman participants on the other. Monkeys and apes made use of all three possible methods of combination, as did the older children, although monkeys and apes used subassembly on a greater proportion of moves than did even the oldest children. Greater use of subassembly was associated with better success at seriation in monkeys and apes, as in children. Like the older children (16 and 21 months), few nonhuman participants exhibited strong reliance on a single method of combination.

One might ask if the nonhuman participants perceived the task in the same way as the human children. For example, children might have adopted stacking as a goal, or they may have had no goal at all. The monkeys and apes might have been working to a specific end point of nested cups, guided by their previous experience in similar contexts (i.e. completing an experimental task for a reward) or because they were copying a model's actions.

Although we cannot rule out some effect of experience across our participant groups, this seems an inadequate explanation of the differences that we found. Regardless of past experience, because all participants engaged in combinatorial activity with the cups, they all had opportunity to demonstrate use of the different combinatorial strategies to produce whatever structures they wished. Our analyses incorporate all combinatorial activity, goal-directed or otherwise, including stacking the cups. As Ruff and Rothbart (1996) note, engagement in an activity is in and of itself evidence that the individual is motivated to achieve a goal, so long as it is 'possible to observe subjects correcting errors, stopping when the task is finished, or halting an unproductive activity' (p. 29).

Moreover, it is highly unlikely that the human demonstrator was more salient to the nonhuman participants than to the human participants. We know that monkeys are very poor at reproducing actions they observe humans performing (Visalberghi & Fragaszy, 1990). Among the genus *Pan,* imitative propensities are not as well developed as in young children, although they may vary somewhat in accord with early rearing experience (e.g. Tomasello, Savage-Rumbaugh & Kruger, 1993; Custance, Whiten & Bard, 1995; Myowa-Yamakoshi & Matsuzawa, 2000). Given that performance by the apes in our study did not vary in accord with rearing experience (Johnson-Pynn *et al.*, 1999), and the performance of the monkeys and apes was statistically equivalent for most variables, it is improbable that the apes, whatever their rearing experience, or the monkeys seriated cups as well as they did because they were copying a model. Thus, we conclude that differences between human and nonhuman participants do not reflect better use of the model by the apes and monkeys to recreate the correct response modeled by the experimenter.

It appears that our nonhuman and human participants arrived at success in this task through parallel behaviors. Both sets of participants produced a variety of combinations in an opportunistic fashion. Persistence alone is not sufficient to achieve seriation if one does not produce a variety of combinations and disassembly to overcome randomly produced errors, as DeLoache *et al.* (1985) pointed out. In the absence of flexible combinatorial methods, seriation can be achieved by rigid use of a single strategy, but individuals attempting seriation in this manner can become derailed by a single error (DeLoache *et al.*, 1985).

Monkeys' and apes' activity, like the activity of 16- and 21-month-old children, appeared to be planful, in Willatts' (1990) sense of that term. That is, the participants performed an action, and then evaluated the outcome of the action with respect to the intended goal (nesting all the cups). If the outcome was not appropriate, they took some remedial action (for example, disassembling the structure or shifting to work on an alternate stack of cups), repeating the cycle until a more appropriate outcome resulted. This view of how activity with the cups was organized applies equally well to the monkeys and apes as to the 16- and 21-month-old children. The youngest children differed in that they apparently did not evaluate the outcome of their actions in relation to the larger goal of seriation of all available cups in any systematic fashion. It may be that they did not recognize achievement of seriation to be a goal or that they had difficulty incorporating multiple physical or behavioral elements in an organized sequence.

Three conceptions of seriation

The ability to seriate five cups has been interpreted as a sensorimotor task that benefits from a working concept of reversibility (DeLoache *et al.*, 1985, Greenfield *et al.*, 1972, Sugarman, 1983). Reversibility in the seriation task is a two-way relationship in which a middle cup is conceived as being smaller than the previous cup and larger than the subsequent cup. Subassembly is one means to instantiate reversibility in action. The hierarchical combination of objects employed in the subassembly method permits efficient seriation, and use of this combinatorial method may indeed be coupled with a conceptual understanding of reversibility. However, this work shows that proficient seriation (achieved by monkeys and apes) can incorporate more diverse action assemblages, and it may be unnecessary to link skill at seriation with abstract conceptions of reversibility. As we observed and DeLoache *et al.* (1985) noted, potting also affords efficient seriation; one can achieve a seriated set in the same number of moves by potting as by subassembly. In principle one can make equally efficient use of both strategies to seriate a set of cups.

Use of subassembly increases with age in children, and is associated within age and across species with success at seriation and at inserting a sixth cup into a seriated five-cup set. We found increased use of subassembly in six-cup trials compared to five-cup trials in both monkeys and apes, as a group, and in children (pooled ages), for those participants that received these trials. Inserting a sixth cup is achieved more efficiently (with fewer moves) by removing and replacing a set of objects than by more complete disassembly and reassembly by potting. These findings support Greenfield *et al.*'s (1972) contention that subassembly reflects an emerging mastery in this task, which is interpreted by Greenfield *et al.* as indicating emergence of hierarchical organization in the service of goal-directed activity. However, the task demands alone in the six-cup trials support increased use of subassembly, independent of a participant's aim to produce hierarchically organized combinations. When a participant removes several cups as a unit, inserts the sixth cup, and then replaces the removed unit back into the working stack, it is subassembly. From the point of view of hierarchical organization of behavior, a multi-cup set handled in this way should not be considered as 'subassembled' in the same sense as in the construction of the original set. Removing a multi-cup unit occurs as one step, whereas assembling a multi-cup unit requires a sequence of actions. We suggest that subassembly does indeed reflect increasing mastery in this task, and certainly contributes to increased success with a sixth cup, but not necessarily because the participant has adopted a qualitatively different combinatorial strategy.

A second way of conceptualizing the contribution of subassembly to mastery of seriating five cups and inserting a sixth cup may be useful in understanding both the developmental progression observed in young children and the good success of our nonhuman participants. The alternative conceptualization is that participants' behavior reflects experientially driven increases in the forms of activity that constrain the degrees of freedom to be managed in the task. The actor reduces the degrees of freedom in this task by reducing the total number of cups still to be placed into the structure. Potting reduces the number of cups by one with each combination. By reducing the number of cups still to be combined by two or more with each successful combination, subassembly reduces degrees of freedom even more quickly than potting. In the sixth-cup condition, using subassembly is especially beneficial because potting is precluded as an effective strategy until the stack is disassembled. Disassembly automatically increases the number of moves necessary to achieve seriation, thereby reducing the probability of success. Thus, for both segments of solution (the initial combination and reconstruction after an error in combination), behaviors that reduce the number of combinatorial steps needed in the future promote achievement of seriation.

The theory of the development of skill in action articulated by Manoel and Connolly (1997) speaks to our concerns with degrees of freedom, the role of variation in activity and the experientially driven basis for skill development in seriation. These authors, attempting to reconcile representational and dynamic systems theories of skill development, propose that action programs can be analyzed at the level of macrostructure and microstructure. For example, in the task of picking up a rod and depositing it into a 'posting box' with a matching hole in the cover, the macrostructure of the action program is to grasp, transport, align, insert and deposit the rod. The microstructure of these actions involves posture, form of grasp and movements of the shoulders, elbows and wrist, among other things. Initially young children exhibit variability ('disorder') at both the macro and micro level of organization in this task. With developing skill, macrostructure becomes stable, but microstructure continues to display variability. Manoel and Connolly, following Bernstein (1967), argue that variability in microstructure, rather than indicating instability of the system or incomplete skill, is in fact the hallmark of skill. Retaining many degrees of freedom at the microstructural level affords many avenues to stability at the macrostructural level. Thus, one can predict that a narrow reliance on a few forms of action at the microstructural level impedes the development of skill. This interpretation aids us in understanding how children relying solely on one method of combining cups can achieve seriation, but these same children are unable to manage the sixth-cup problem (DeLoache *et al.*, 1985). It also informs our findings that 11-month-old children, who used one form of combination in more than half of their moves, virtually never succeeded in seriating five cups, whereas 16- and 21-month-old children used all the methods of combination more evenly and succeeded more often.

The variation in activity we observed in our participants is significant for skill development because it is necessary for the discovery of effective activity. Experientially driven modulation of varying action can lead to improvements in skill. The representational conception of the task (in terms of reversibility) may follow, rather than lead, mastery of seriating cups in both the five-cup and sixth-cup versions of the task. This is not to say that conceptual sophistication about the properties of objects and how they can be combined is irrelevant to performance when challenges are introduced. It is only to say that conceptual sophistication is not needed for initial mastery of the task in a basic and unvarying format (that is, seriating five familiar nesting cups).

The dynamic motor praxis explanation of skill development outlined above is congruent in many ways with the hierarchical development of skill conceptualized by Case (1992) and by Fischer (1980; Bidell & Fischer, 1994), which provides a third conception of seriation. The developmental progression of actions with multiple cups, from acts with single cups, to combinations of two cups (pairing), to combinations of three or more cups (potting and subassembly) that we and others observed in young children fits nicely into contemporary neo-Piagetian models of cognitive development. For example, Case (1992) proposes that the construction of cognitive skills moves repeatedly across development from actions with singular elements to actions integrating multiple elements, first sequentially and then simultaneously. In the terms of Case's theory, proficient seriation with nesting cups would not require a specific conceptual structure (e.g. reversibility) but rather an effective means of organizing action with multiple demands. Denise Reid (1992) uses a similar argument to interpret children's gradual mastery of moving an object in varied directions with relation to body axes. Reid asked children to move a rod through a maze in straight-ahead, full left or full right direction with respect to the frontal body plane (a single-element directional problem), or through a diagonal vector. One has to combine two or more directional elements simultaneously to achieve the diagonal movement, and this was much more difficult for young children than were any of the three single-direction problems.

On the basis of Case's (1992) theory, we predicted that our youngest participants would exhibit pairing actions, moving one cup at a time, in accord with Case's indication that children between 8 and 12 months old typically function at his level 1.2. Monitoring structures arising and working to create a stable structure, characteristic of Case's level 1.3, would be evident in a shift from pairing to potting in the middle age group. Finally, an ability to deal with two relational structures simultaneously (level 2.1) would enhance the likelihood of using subassembly, which as we have seen promotes the construction of structures with three or more cups. We expected to see this process beginning in our oldest age group. Our findings match the first two predictions rather well, but the third is less clearly supported. Twenty-one-month-olds did not use subassembly proportionally more frequently than 16-month-olds. Apparently more experience than our procedure provided is needed for children of this age to master the multiple relations presented in the seriation task.

Comparative analysis: why did the monkeys and apes do better than the children?

Both chimpanzees and capuchins combine objects in their spontaneous activities at an unusually high rate compared to other primates (Torigoe, 1985). In captivity, these propensities frequently lead to the use of objects as tools in both genera. Fragaszy and Adams-Curtis (1991) have emphasized the probable value of both combinatorial manipulation and generative manipulation in the discovery of tool use in capuchins. The discovery of using objects as tools is less frequent in natural settings than in captivity for chimpanzees and even more so for capuchins, but combinatorial proclivities still contribute substantially to each genus's typical modes of foraging. Combination of one object with a substrate is the most common form of combinatorial activity in captive capuchins and chimpanzees (Takeshita & Walraven, 1996; Fragaszy & Adams-Curtis, 1991). In natural environments, capuchins habitually pound hard-husked nuts, fruits or invertebrates (such as snails) on tree limbs or stones to break them open (Janson & Boinski, 1992). Similarly, chimpanzees pound nuts on hard surfaces, often with the assistance of a stone or section of a branch as a hammer (Boesch-Ackermann & Boesch, 1993; Inoue-Nakamura & Matsuzawa, 1997).

The manipulative propensities of the nonhuman primates in our study most likely contributed to their good success at seriating cups, but we must step back a moment to appreciate the role of combinatorial manipulation *per se* for mastery of the seriation challenge for the young children. Fenson *et al.* (1976) documented that combinatorial actions occur routinely in young children 13 and 20 months old who were provided with an assortment of objects (on average 26 to 27 combinatorial actions per 20-minute observation session), although these authors did not differentiate actions combining two objects from actions combining three or more objects. It would be useful to have information on spontaneous rates of combinatorial manipulation in young children to match with activity when nesting cups are presented. We predict that the rate and perhaps also the pattern of micro-developmental progressions toward mastery of seriation with the nesting cups will reflect the combinatorial proclivities of the participant at the time that mastery appears.

Apes and monkeys readily mastered this task with the limited practice provided to them but the same amount of practice did not have the same effect for young children. It is unlikely that monkeys and apes do better than children because they are more likely to recognize reversibility of the cups' sizes, or because they are more likely to produce multi-cup structures using subassembly. As we have seen, they produced the same proportion of multi-cup structures as the children at 16 and 21 months of age. We propose one other possibility that we view as more likely than the two listed previously: monkeys and apes are better able to make use of action-outcome links than are young children. We think this may occur because the nonhuman participants we tested are, as older juveniles and adults, already 'practiced' with their bodies. The exercise of moving objects does not, of itself, challenge their ability to control their bodies. Young children, on the other hand, must attend more effortfully to sitting upright, to maintaining erect posture while reaching out, to prehending the cups and putting them into combination with others without knocking apart the existing structure, and so on. Every step of the task requires some amount of concentration for the novice mover. This is probably part of the appeal of the task for the young child, after all – it is challenging but possible.

Apes and monkeys had also to master the finer points of combining the cups, which were probably more novel for them than for children, given the difference between these groups in everyday experience with small portable objects. Even so, monkeys and apes achieved adequate control of their actions and of the cups with minimal practice.

The dynamic motor praxis explanation of differences in rate (and in short term, degree) of mastery leads to the prediction that, for a given motor skill, the individual (of whatever species) facing fewer new motor praxis demands will master the task more quickly (Bernstein, 1967; Thelen & Smith, 1994). To the extent that improving skill involves less effortful management of multiple degrees of freedom in movement, improving skill permits more attention to perceiving action-outcome links and organizing a response to errors. A similar argument can be made for the manner in which children master other skills that involve combining objects, such as using a spoon (Connolly & Dalgleish, 1989) or a hook tool (Brown, 1990). All these findings suggest that humans first master the use of objects in specific contexts, and then subsequently, as a function of increasing mastery, refine our conceptualization of the tasks in which we use objects. In other words, specific perceptual and motor learning proceeds, and perhaps enables, contemplative refinement in the instrumental domain, a process that Johnson (1987) suggests happens more generally in cognition than we are wont to recognize.

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References

Bernstein, N. (1967). *The coordination and regulation of movement*. London: Pergamon Press.

Bidell, T.R., & Fischer, K.W. (1994). Developmental transitions in children's early on-line planning. In M.M. Haith & J.B. Benson *et al.* (Eds.), *The development of future-oriented processes. The John D. and Catherine T. MacArthur Foundation series on mental health and development* (pp. 141–176). Chicago: University of Chicago Press.

Boesch-Ackerman, H., & Boesch, C. (1993). Tool use in wild chimpanzees: new light from dark forests. *Current Directions in Psychological Science*, **2** (1), 18–21.

Brown, A.L. (1990). Domain-specific principles affect learning and transfer in children. *Cognitive Science*, **14** (1), 107–133.

Case, R. (1992). *The mind's staircase: Exploring the conceptual underpinnings of children's thought and knowledge*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Case, R., & Okamoto, Y. (1996). The role of central conceptual structures in the development of children's thought. *Monographs of the Society for Research in Child Development*, **61** (1–2, Serial No. 246).

Connolly, K., & Dalgleish, M. (1989). The emergence of a tool-using skill in infancy. *Developmental Psychology*, **25** (6), 894–912.

Custance, D.M., Whiten, A., & Bard, K.A. (1995). Can young chimpanzees (*Pan troglodytes*) imitate arbitrary actions? Hayes & Hayes (1952) revisited. *Behaviour*, **132** (11–12), 837–859.

DeLoache, J.S., Sugarman, S., & Brown, A.L. (1985). The development of error correction strategies in young children's manipulative play. *Child Development*, **56** (4), 928–939.

Fenson, L., Kagan, J., Kearsley, R.B., & Zelazo, P.R. (1976). The developmental progression of manipulative play in the first two years. *Child Development*, **47** (1), 232–236.

Fischer, K.W. (1980). A theory of cognitive development: the control and construction of hierarchies of skill. *Psychological Review*, **87** (6), 477–531.

Fragaszy, D.M., & Adams-Curtis, L.E. (1991). Generative aspects of manipulation in tufted capuchin monkeys (*Cebus apella*). *Journal of Comparative Psychology*, **105** (4), 387–397.

Greenfield, P. (1991). Language, tools, and the brain: the ontogeny and phylogeny of hierarchically organized sequential behavior. *Behavioral and Brain Sciences*, **14** (4), 531–595.

Greenfield, P., Nelson, K., & Saltzmann, E. (1972). The development of rulebound strategies for manipulating seriated cups: a parallel between action and grammar. *Cognitive Psychology*, **3** (2), 291–310.

Inhelder, B., & Piaget, J. (1969). *The early growth of logic in the child*. New York: Norton.

Inoue-Nakamura, N., & Matsuzawa, T. (1997). Development of stone tool-use by wild chimpanzees (*Pan troglodytes*). *Journal of Comparative Psychology*, **111** (2), 159–173.

Janson, C.H., & Boinski, S. (1992). Morphological and behavioral adaptations for foraging: the case of the Cebines. *American Journal of Physical Anthropology*, **88**, 483–498.

Johnson, M. (1987). *The body in the mind: The bodily basis of meaning, imagination, and reason*. Chicago: University of Chicago Press.

Johnson-Pynn, J.S. (1999). Social interaction affects preschoolers' performance in tool use tasks. *Dissertation Abstracts International*, **60** (11), 5811B. (University Microfilms No. AAT99-49508)

Johnson-Pynn, J., Fragaszy, D.M., Hirsh, E.M., Brakke, K.E., & Greenfield, P.M. (1999). Strategies used to combine seriated cups by chimpanzees (*Pan troglodytes*), bonobos (*Pan paniscus*), and capuchins (*Cebus apella*). *Journal of Comparative Psychology*, **113** (2), 137–148.

Keppel, G. (1991). *Design and analysis: A researcher's handbook* (3rd edn.). Englewood Cliffs, NJ: Prentice-Hall.

Kleinbaum, D.G., Kupper, L.L., & Muller, K.E. (1987). *Applied regression analysis and other multivariate methods*. Kent, OH: Kent Publishing Company.

Langer, J. (1986). *The origins of logic. One to two years*. Orlando, FL: Academic Press.

Manoel, E., & Connolly, K.J. (1997). Variability and stability in the development of skilled actions. In K.J. Connolly & H. Forssberg (Eds.), *The neurophysiology and neuropsychology of motor development: Clinics in developmental medicine 143/144* (pp. 286–318). London: Max Keith Press.

Myowa-Yamakoshi, M., & Matsuzawa, T. (2000). Imitation of intentional manipulatory actions in chimpanzees (*Pan troglodytes*). *Journal of Comparative Psychology*, **114** (4), 381–391.

Reid, D. (1992). Horizontal and vertical structure: stages and substages in children's motor development. In R. Case (Ed.), *The mind's staircase: Exploring the conceptual underpinnings of children's thought and knowledge* (pp. 247–266). Hillsdale, NJ: Erlbaum.

Ruff, H.A., & Rothbart, M.K. (1996) *Attention in early development: Themes and variations.* New York: Oxford University Press.

Savage-Rumbaugh, E.S. (1986) *Ape language: From conditioned response to symbol*. New York: Columbia University Press.

Savage-Rumbaugh, E.S., Murphy, J., Sevcik, R.A., Brakke, K.E., Williams, S.L., & Rumbaugh, D.M. (1993) Language comprehension in ape and child. *Monographs of the Society for Research in Child Development*, **58**, (3–4, Serial No. 221).

Savage-Rumbaugh, E.S., Shanker, S.G., & Taylor, T.J. (1998). *Apes, language, and the human mind*. New York: Oxford University Press.

Sinclair, H., Stambak, M., Lezine, I., Rayna, S., & Verba, M. (1989). *Infants and objects: The creativity of cognitive development*. San Diego: Academic Press.

Sugarman, S. (1983). *Children's early thought: Developments in classification*. New York: Cambridge University Press.

Takeshita, H., & Walraven, V. (1996). A comparative study of the variety and complexity of object manipulation in captive chimpanzees (*Pan troglodytes*) and bonobos (*Pan paniscus*). *Primates*, **37** (4), 423–441.

Thelen, E., & Smith, L.B. (1994). *A dynamic systems approach to the development of cognition and action*. Cambridge, MA: MIT Press.

Tomasello, M., Savage-Rumbaugh, E.S., & Kruger, A.C. (1993). Imitative learning of actions on objects by children, chimpanzees, and enculturated chimpanzees. *Child Development*, **64** (6), 1688–1705.

Torigoe, T. (1985). Comparison of object manipulation among 74 species of nonhuman primates. *Primates*, **26** (2), 182–194.

Visalberghi, E., & Fragaszy, D.M. (1990). Do monkeys ape? In S.T. Parker & K.R. Gibson (Eds.), *'Language' and intelligence in monkeys and apes: Comparative developmental perspectives* (pp. 247–273). New York: Cambridge University Press.

Visalberghi, E., Fragaszy, D.M., & Savage-Rumbaugh, E.S. (1995). Performance in a tool-using task by common chimpanzees (*Pan troglodytes*), bonobos (*Pan paniscus*), and capuchin monkeys (*Cebus apella*). *Journal of Comparative Psychology*, **109** (1), 52–60.

Willatts, P. (1990). Development of problem-solving strategies in infancy. In D.F. Bjorklund *et al.* (Eds.), *Children's strategies. Contemporary views of cognitive development* (pp. 23–66). Hillsdale: Erlbaum.

Woodward, W.M. (1972). Problem-solving strategies of young children. *Journal of Child Psychology and Psychiatry*, **13**, 11–24.

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