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Experience and Materials Affect Combinatorial Construction in Tufted Capuchin Monkeys (*Cebus apella*)

Carrie R. Rosengart and Dorothy M. Fragaszy
University of Georgia

Three movement procedures can combine nesting cups into seriated structures. Reliance on these procedures changes with age in human children, and the putatively most advanced emerges as a predominant procedure at 3 or more years. Six monkeys' (*Cebus apella*) combinatorial procedures and successes at nesting seriated cups were evaluated. The current study examined whether the procedures used (a) shift toward more efficient procedures after unguided experience, (b) are dependent on the type of object being combined, and (c) can be altered by specific training history. All factors produced a change in procedure for some individuals, suggesting that combinatorial procedure is a product of the dynamic influences of preexisting tendencies to act in certain ways, of environmental circumstances, and of prior experiences. Some monkeys preferred the putatively most cognitively complex procedure.

Action rules allow the primate to manipulate a broad class of objects in a particular manner rather than having to learn a new behavior pattern for each particular object in that class. The development of rule-guided manual activity in children has been explored with the use of seriated cups (Greenfield, Nelson, & Saltzman, 1972). Three main combinatorial procedures (see Figure 1) were identified by Greenfield et al. (1972). The simplest procedure is the *pair,* in which nesting or stacking combines one cup with another. The two more complex procedures require that three or more cups be combined. In the *pot* procedure, the actor combines two or more cups with another cup by moving one cup at a time; thus, only a single cup is the active unit. In potting, one cup is placed inside two or more cups. The other procedure, *subassembly,* occurs when two or more cups become a subunit and the subunit is combined with one or more other cups. With this procedure, the subunit is transformed from the acted-upon object to the active object. The two key features of subassembly are that (a) an item that was once a receiving object is transformed into an active object and (b) the multicup structure now functions as a single item. Greenfield et al. considered this procedure the most complex because it requires a hierarchical combination of multiple cups.

In children, particular procedures occur as the dominant method of combining cups in a sequential order, with the pair procedure dominant at 11 months, the pot procedure dominant at 20 months, and the subassembly procedure emerging as dominant at 36 months. Greenfield and colleagues (Greenfield, 1991; Greenfield et al., 1972) suggested that this developmental sequence is not only correlated with the development of language but also controlled by the same underlying mechanism. Language also progresses from combinations of two words (pair), to sentences with multiple, parallel phrases (pot), and then to sentences with multiple phrases joined on the basis of their relation to one another (subassembly). Pepperberg (2001) noted a similar pattern in the use of words and spontaneous object combinations in a young grey parrot.

Combinatorial manipulation has been examined in nonhuman primates with varying results (Matsuzawa, 1991; Westergaard, 1992, 1993, 1999; Westergaard & Suomi, 1994). Johnson-Pynn, Fragaszy, Hirsh, Brakke, and Greenfield (1999) investigated the procedures used by chimpanzees (*Pan troglodytes*), bonobos (*Pan paniscus*), and capuchins (*Cebus apella*) to combine seriated cups. They found that all three species were able to create a seriated five-cup structure with variable-sized nesting cups. All three species displayed all of the combinatorial procedures that had been previously identified in humans, and there was no difference among the species in the procedures that they used to complete the task. The language-trained apes in Johnson-Pynn et al.'s study used the subassembly procedure at the same rate as the other apes and monkeys. In the only other report on combinatorial manipulation of nesting cups in a chimpanzee (Matsuzawa, 1991), an adult chimpanzee with language training showed a preference for subassembly.

In short, nonhuman primates, both with and without language training, perform equally on this task, and some do so in a manner similar to humans old enough to speak. As language ability does not appear to be necessary for the developmental progression in object combination, what then explains the existence of preferred procedures and the transitions between these preferences? Although the hierarchical combinations of words into sentences may be organized in the same manner as objects are combined into structures, the underlying process is clearly more general and phylogenetically more widely distributed than language. Perhaps the way that objects are combined can be viewed as a dynamic

Carrie R. Rosengart and Dorothy M. Fragaszy, Department of Psychology, University of Georgia.

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Correspondence concerning this article should be addressed to Carrie R. Rosengart, Department of Psychology, University of Georgia, Athens, GA 30602-3013. E-mail: crosenga@uga.edu

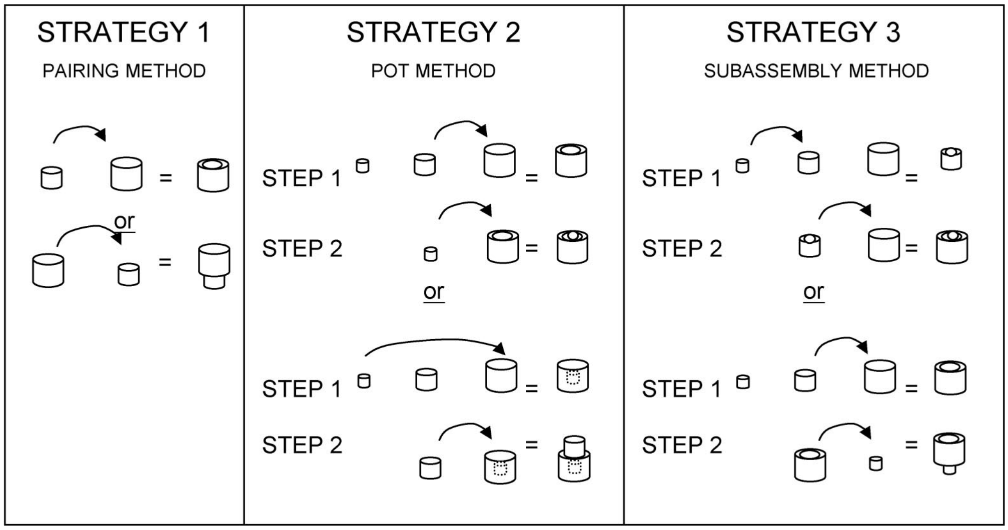


Figure 1. Procedures used for combining cups as identified by Greenfield, Nelson, and Saltzman (1972). Adapted from *Cognitive Psychology,* Vol. 3, P. M. Greenfield, K. Nelson, and E. Saltzman, "The Development of Rulebound Strategies for Manipulating Seriated Cups: A Parallel Between Action and Grammar," p. 295, Copyright 1972, with permission from Elsevier.

interaction between the natural tendencies of the individual, the result of past actions, and the demands of the objects themselves. Goal-directed actions can be seen as the product of movements with many degrees of freedom, and changes in any one of these degrees of freedom can impact the resulting behavior (Thelen & Smith, 1994). Only a limited number of actions will be organized from all of the possible combinations because multiple influences (within a given range) will result in the same behavioral outcome and because biomechanical constraints rule out some variations.

In an analogy of a ball falling down a slope, all possible behavioral forms in a given context can be viewed as a landscape with multiple valleys (Thelen & Smith, 1994). Depending on the specific environmental and experiential circumstances, the ball will be close to and fall into a single one of these valleys, and a single resulting behavior will be displayed. The valley down which the ball rolled is termed an *attractor basin,* which can be viewed like a funnel. If particular influences result in a behavior moving to anywhere within the area of the funnel, the resulting behavior will fall in the same funnel each time, resulting in the same action even when the situation slightly differs. Each time a behavior occurs, it becomes more likely that the same behavior will be repeated in future encounters with similar circumstances. A stable, single attractor basin where the same outcome is predicted, even in varying environmental conditions, can then represent development and skill mastery.

As a behavioral system develops, a single attractor can split into two behavior outcomes. This allows for new behavioral outcomes to emerge as an individual gains experience. With expertise in an area, an individual can detect important environmental distinctions and respond differentially in a situation-appropriate manner (Thelen & Smith, 1994).

An attractor landscape describing the combination of cups into stable structures would feature pair, pot, and subassembly attractor basins. As each procedure is used, there is a greater likelihood that it will be used again. This experience can come from explicit experimental sessions, as is the case with monkeys in a laboratory setting where there are no other opportunities to encounter similar situations. However, in humans, there are opportunities for learning about combining objects in many typical activities, such as when a child plays with his or her own set of nesting cups, plays with blocks or kitchen objects, or has a pretend tea party, for example.

The model presented in the preceding paragraph predicts that each individual will develop a procedural preference, but it does not explain the transition from one preferred mode of acting to another. Transitions could be understood to reflect the actor's growing ability to detect the efficiency of each procedure. Pairing is the least efficient because it is impossible for a stable structure with more than two cups to be created using solely this procedure. Both potting and subassembly can result in a multicup stable structure. However, they differ in efficiency in terms of the number of movements. If a paired structure is brought as a subunit to the next object to be combined, an individual simply shifts the stack of cups in a single motion to the next object. In comparison, with potting, the individual must first reach for each new object to be combined and then bring that object to the working stack of cups. This results in twice as many body movements per combinatorial action when using the pot procedure as compared with the subassembly procedure.

An efficiency model alone, however, cannot fully explain combinatorial behavior as it has been observed in human and nonhuman primates. An efficiency model would predict an initial period in which individuals have no procedural preference when facing a novel task before the relative strengths of each procedure could be learned. Even in the first eight trials with variable-sized cups, monkeys, apes, and children showed preference for certain procedures (Greenfield et al., 1972; Johnson-Pynn et al., 1999). The dynamic systems theory would explain initial procedural preference as dependent on the starting condition of the "system"—that is, intrinsic characteristics of the individual that reflect biological constraints (strength, postural control, stamina, etc.) and prior experience—and on the features of the materials.

A traditional associative learning framework could be used to interpret the role of experience, but like the efficiency model, it is inadequate to explain initial preferences. Additionally, an individual's preferences for particular combinatorial procedures can change absent reinforcement or punishment. According to a dynamic systems explanation, this change may occur because of the repetition of the behavior and not necessarily because of the specific contingencies associated with the behavior.

On the basis of a dynamic systems perspective, with increasing experience being the most efficient of the combinatorial procedures, subassembly should be preferred. Although the less efficient procedures should decrease, they will not disappear entirely unless the individual is able to seriate the cups without a sequence error. However, no single preferred procedure will always be the most appropriate one for fixing a mistake in the order of the cups. As each cup is moved, on the basis of the structures already constructed, the particular characteristics of that situation will determine which combinatorial procedure is best suited for each move.

The purpose of this study was to explore a dynamic systems explanation of the development of seriation in tufted capuchin monkeys. Studying 6 monkeys, we examined how individual propensities, the characteristics of the object, and prior experience affected each monkey's combinatorial activity. In Experiment 1, we looked at the way the monkey's success and combinatorial procedure changed with experience. It was expected that the monkeys would seriate the cups more readily with experience. This improvement would be reflected in the number of completed structures (all five cups combined into a single stable set of cups that would remain cohesive without being held together by the monkey) but not the number of moves required to construct that structure, as seriation can be achieved by repeated efforts to combine the cups and does not require the monkey to understand the ordinal relations of the objects. We also predicted that with increasing experience, the monkeys would rely less on the pair procedure relative to the more efficient pot and subassembly procedures. Moreover, as the monkeys become experts, the dominant procedure should be subassembly because this method, in principle, achieves seriation with the fewest discrete arm movements. This prediction follows from the assumption that the actor minimizes energy expenditure as skill increases (e.g., Bernstein, 1996). The number of object placements may not differ, but the number of arm movements is different between potting and subassembly.

Previous research has used variable-sized cups to probe the development of combinatorial behavior (e.g., Greenfield et al., 1972; Johnson-Pynn et al., 1999; Matsuzawa, 1991). Although these objects provide an effective method of eliciting structure formation, they also require the objects to be combined in a specific order for successful completion of a stable structure. In Experiment 2, combinatorial procedure is viewed absent the added demand of seriation in tufted capuchin monkeys. Same-sized cups, which can nest together in any order to form a structure, can be combined by using all of the previously identified procedures. This allows combinatorial activity to be viewed in terms of the active and passive roles of each object, where any of the objects would be able to serve in either of these roles for any potential combinations of cups.

Without the requirements for placing the cups in a particular order, it should be easier for the monkeys to create structures. With the variable-sized cups, there is a chance that the individual would make an error, placing a cup in the wrong order, which would require an adjustment of the object and possibly prompt a shift in procedure. In dynamic systems terms, an error creates new circumstances that can result in a shift toward a different attractor basin, thus provoking a shift in behavior. The same task with same-sized cups would not provoke a shift in procedure, permitting a stronger preference for a specific procedure of combinatorial behavior. Of the two procedures that will allow the creation of structures with more than two objects (pot and subassembly), the monkey should not change the order of procedural preference when seriation is not required. Thus, we predicted a difference between outcomes in Experiment 1 (with variable-sized cups) and Experiment 2 (same-sized cups). In Experiment 1, we predicted a shift in procedures with experience. In Experiment 2, we predicted that the distribution of procedures would not change and thus would differ from Experiment 1.

In Experiment 3, the monkeys were given specific training in the subassembly procedure and then retested. According to dynamic systems theory, the training experience would strengthen the attractor basin for subassembly and lead to a greater use of the procedure in the future. We predicted that the monkeys would shift their preferred procedure toward a preference for subassembly after this training. This would demonstrate that the procedure used to combine cups reflects recent experience rather than a preexisting central cognitive mechanism.

Experiment 1: Expertise

Method

Subjects and Housing

The subjects in this experiment were 2 young adult, male capuchin monkeys (*Cebus apella*), Nick and Leo, who were both 7 years old. Both monkeys had no prior experience with nesting cups. These monkeys were housed as a pair in indoor cages at the University of Georgia. Twice a day subjects were fed Lab Diet monkey chow and various types of fruit. Water was available ad libitum.

Apparatus

Two sets of cups were used. One set contained five cups of the same size that were made of stainless steel (Vollrath Co., Sheboygan, WI). The height of each cup was 3.5 cm with a 6.0-cm diameter at the top, narrowing to a 4.0-cm diameter at the bottom. Any cup could be nested into any other cup (see Figure 2a). The second set of cups consisted of children's plastic nesting cups (Kiddie Products, Avon, MA) that differed in color and size. The six smallest of these cups were used, which ranged in height from 3.0 cm to 4.0 cm and in diameter from 4.0 cm to 7.0 cm. These cups had straight sides and could only fit together in one order. The third smallest cup of these six was not used (see Figure 2b). The third cup was omitted to permit subsequent testing for insertion into a completed structure as a)

b)

Figure 2. a: A set of stainless steel same-sized cups. b: A set of plastic variable-sized cups.

presented by Johnson-Pynn et al. (1999). These trials were conducted during this experiment but are not reported here, as the results replicated the findings of Johnson-Pynn et al.

The objects were presented to the monkeys in a stainless steel mesh testing cage with a clear Plexiglas front panel (77 cm × 46 cm × 64 cm). An opening (10 cm × 6 cm) in a clear Plexiglas sliding door (19 cm × 18 cm) in the front panel allowed for presentation of the cups in the testing cage and retrieval of the objects. All testing trials were recorded with a video camera that faced the front of the testing cage.

Procedure

Training Phase 1. The training procedure was the same as that used by Johnson-Pynn et al. (1999), with the exception that the earlier study used variable-sized cups for training whereas in the current study the monkeys were trained with same-sized cups. Each subject was initially trained to combine same-sized cups to form a single stable structure. They were first taught to give a single cup back to the experimenter. They were then given two of the same-sized cups and rewarded for creating a two-cup structure. Nick and Leo learned to combine two cups after 16 and 14 training sessions, respectively. After they succeeded at this step, additional cups were presented, increasing one cup at a time until the subjects were able to complete a five-cup structure. Nick completed this training phase in a total of 19 sessions, and Leo completed training after 17 sessions. The criterion for advancing from each of these five training steps was the construction of six consecutive complete structures. Each time a structure was completed, the monkey was rewarded with a small piece of dried fruit or cereal regardless of the procedure used to create that structure, as in Johnson-Pynn et al.'s procedure.

Testing Phase 1—Novice. After completing training, each subject was given eight trials with five variable-sized cups. Each test trial was approximately 3 min. A trial ended with the completion of a five-cup structure or when the subject finished the activity (stopped manipulating the cups or gave them back to the experimenter). Multiple trials were given in a single session if the subject was still attentive to the task. Subjects were given verbal encouragement during the trial and a food reward at the end of each trial regardless of performance, as in Johnson-Pynn et al. (1999).

Training Phase 2. Nick and Leo were provided additional exposure to the variable-sized cups in this phase to allow familiarity. Familiarity was determined on the basis of the subject's ability to combine two of the variable-sized cups by pairing, demonstrating the ability to place one cup, stacked or nested, in another cup in six consecutive attempts. The monkeys did not stop acting with the cups until they were nested. Although stacking was sufficient to satisfy the experimenters, it was not sufficient for the monkeys. Leo passed this training phase immediately, reaching the criterion in one session. Nick required additional training following his first exposure to the nesting cups. Initially he simply released one cup on top of the other, which was sufficient with the same-sized cups because the shape of the cups allowed them to slide into each other. He was given two randomly selected variable-sized cups at a time until he was able to pair them successfully six consecutive times. This training took three sessions for Nick.

Testing Phase 2—Acclimated. Nick and Leo were again given eight testing trials with the variable-sized cups. The same procedure as in Phase 1 was used.

Training Phase 3. Nick and Leo were trained to become experts, which was defined by their ability to create a seriated five-cup structure on six consecutive trials. Randomly selected variable-sized cups were presented. First, two cups were given. After they reached criterion (six consecutive successes) with combining the two cups, three cups were presented. Additional cups were added after criterion was reached at each level until the monkeys combined five variable-sized cups to create a single stable structure with all available cups for six consecutive trials.

Testing Phase 3—Expert. Nick and Leo were again tested with the same procedure as in Testing Phase 2.

Scoring and Analysis

All testing trials were scored by using the Observer Base Package for Windows (1996). For each testing trial, the procedures used in combining the cups were noted: pairing two cups (pair), placing one cup into a structure containing two or more cups (pot), and placing two or more cups as a unit into one or more cups (subassembly) (Greenfield et al., 1972). Johnson-Pynn et al. (1999) used a sequential-moves analysis, which looked at the final moves used to create a structure, as in Greenfield et al. (1972), and an individual-moves analysis, in which each move with the cups was recorded. The current study used the individual-moves analysis, which provides a detailed account of the monkeys' behaviors throughout all of the combinatorial activity. Because, by definition, the first move could only be scored as a pair, as there were no multicup structures present to be manipulated, one pair move was subtracted from each trial. This resulted in a total of eight pairs being subtracted from each phase.

Each monkey's behavior was analyzed in relation to its actions on each of the three phases. Chi-square goodness-of-fit analyses were used to determine whether each individual used the three procedures in a manner different from chance. If an individual showed a nonrandom pattern of procedural choice, post hoc analysis was done to determine the specific order of preference.

Test Phases 1, 2, and 3 were compared for both individuals by using two 2 × 3 chi-square tests of independence. If the pattern of choice of procedure was different between phases, post hoc analysis was conducted to determine where differences lay. The number of moves per phase was also compared for each individual by using a chi-square goodness-of-fit test.

The number of significant post hoc analyses were weighed against the total number of post hoc comparisons with a binomial test, assuming that there would be a .05 chance for a spurious significant finding in each analysis. This determined the probability that the number of significant post hoc results in this experiment would have occurred by chance. To evaluate microdevelopmental shifts accompanying experience with stacking multiple cups, we plotted the proportion of moves in each category for each testing phase for each subject.

Results

Initial Activity With Same-Sized Cups

To assess the monkeys' initial combinatorial activity, we scored the first eight training trials in which the monkeys encountered three same-sized cups for combinatorial procedure and to determine whether they could create a stable structure. Three cups is the minimum requirement for potting and subassembly. Both monkeys exhibited little combinatorial activity. Leo paired eight times, used subassembly twice, and created only two stable three-cup structures in the eight trials. Nick also paired eight times, used subassembly four times, and created four stable three-cup structures in the eight training trials. Neither monkey used the potting procedure.

Activity With Variable-Sized Cups

Both of the subjects constructed variable-sized, five-cup seriated structures, although neither achieved this during the first testing series. On the second testing series, both monkeys were able to complete a five-cup structure on three of the eight trials. Nick completed the five-cup structure on all of the test trials in Phase 3. Leo constructed a five-cup structure on six of the eight test trials in Phase 3.

Both Nick and Leo increased the total number of moves per testing phase with experience, $\chi^2(2, N = 491) = 396.37$, and $\chi^2(2, N = 259) = 106.22$, respectively, $ps < .05$. Nick used 28 moves in Phase 1, 95 moves in Phase 2, and 368 moves in Phase 3. Leo used 25, 75, and 159 moves in these same phases.

Nick used the combinatorial procedures in differing frequencies for Testing Phase 1, $\chi^2(2, N = 28) = 14.21$, $p < .05$, and Testing Phase 3, $\chi^2(2, N = 368) = 55.85$, $p < .05$, but not in Phase 2, $\chi^2(2, N = 95) = 5.20$, $p < .07$. In Phase 1, he showed a significant preference for subassembly over potting, $\chi^2(1, N = 13) = 13.00$, $p < .05$, and for pairing over potting, $\chi^2(1, N = 15) = 15.00$, $p < .05$, but no difference between subassembly and pairing, $\chi^2(1, N = 28) = 0.14$, $p = .71$. In Phase 3, when Nick was considered an expert at combining cups, he used the potting procedure more than pairing, $\chi^2(1, N = 196) = 32.65$, $p < .05$, and subassembly more than pairing, $\chi^2(1, N = 230) = 56.50$, $p < .05$, but he did not use subassembly significantly more often than potting, $\chi^2(1, N = 310) = 3.73$, $p = .053$ (see Table 1).

Leo did not show a preference for any of the three identified procedures in Testing Phase 1, $\chi^2(2, N = 25) = 3.92$, $p = .15$, or Testing Phase 2, $\chi^2(2, N = 75) = 2.24$, $p = .32$; but he used the procedures in a manner different from chance in Testing Phase 3, $\chi^2(2, N = 159) = 17.09$, $p < .05$. In this phase, he had a specific preference for subassembly over pairing and potting procedures, $\chi^2(1, N = 159) = 14.97$, $p < .05$, which did not differ from each other, $\chi^2(1, N = 83) = 2.71$, $p > .05$ (see Table 1).

Table 1
Number of Moves of Each Combinatorial Procedure Exhibited by Nick and Leo in Experiment 1: Expertise

Phase	Procedure			Total	
	Pair	Pot	Subassembly	(N)	$\chi^2(2)$
Nick					
1: Novice	15[a]	0	13[a]	28	14.21
2: Acclimated	28	25	42	95	5.20
3: Expert	58	138[a]	172[a]	368	55.58
Leo					
1: Novice	12	4	9	25	3.92
2: Acclimated	27	19	29	75	2.24
3: Expert	49	34	76[a]	159	17.09

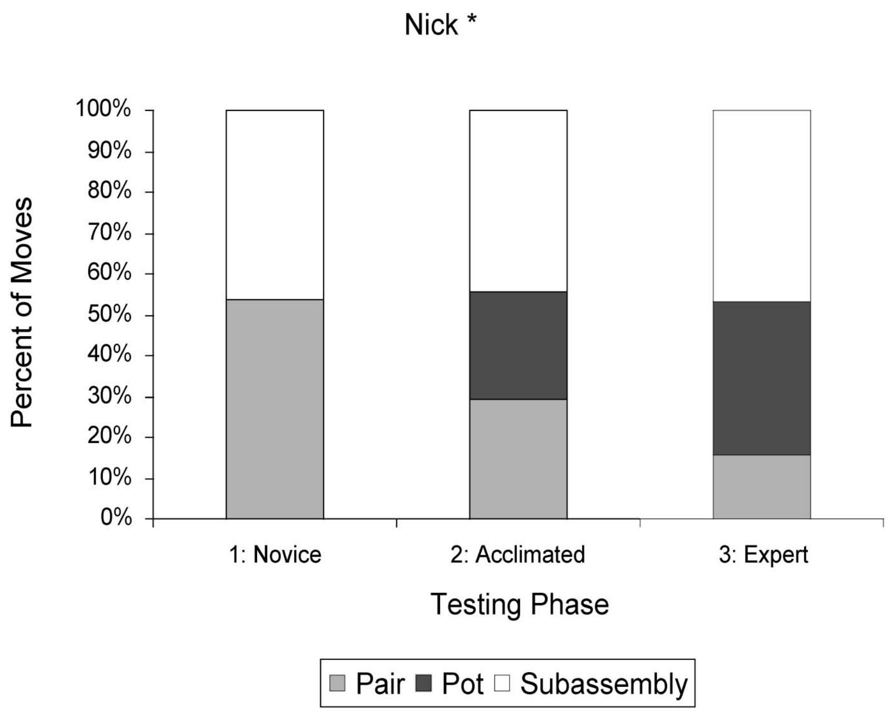
[a] Indicates the procedure used the most frequently ($p < .05$) based on a chi-square test, where $df = 1$. If two procedures are marked, they were used at the same rate, but more than the remaining procedure.

The pattern of procedure used differed significantly depending on the level of experience for Nick, $\chi^2(4, N = 491) = 35.43$, $p < .05$, but not significantly for Leo, $\chi^2(4, N = 259) = 4.19$, $p = .38$ (see Figure 3). On the basis of a residual analysis (Siegel & Castellan, 1988), Nick used pairing more often than expected as a novice. However, when acclimated and as an expert, Nick used pairing less than expected. Nick used potting less than would be expected as both a novice and as an expert (see Table 2). On the basis of the binomial probability of obtaining 11 out of 18 significant post hoc findings ($p = 1.09 \times 10^{-10}$), there are more significant results than would be expected by chance.

Discussion

Both of the monkeys learned to create a seriated five-cup structure even though they were not taught any seriation procedures nor rewarded for their usage. The initial training that the monkeys received was sufficient for the monkeys to perceive that the task was to create a structure by using all of the cups that were available. They were unsuccessful at the task of seriation on their first exposure apparently because these cups were novel to them. Because they had straight sides, the variable-sized cups required more precise alignment to fit together, which made combining the variable-sized cups somewhat more difficult than combining the same-sized cups. Once the two monkeys were familiar with the variable-sized cups from encountering them in pairs, they could create a hierarchically organized structure when five cups were presented, and this ability improved with experience.

Both of the monkeys increased the number of moves that they used in each testing series. If they were learning to seriate the objects more efficiently, there should have been a decrease in total moves, but this was not the case. Rather, it appears that experience taught perseverance. The monkeys were more attentive to the task and produced more moves per bout in a trial before returning the cups to the experimenter to mark the end of their efforts. As trial-and-error combinations of the cups in varying orders could achieve success (i.e., a five-cup structure), the more moves per



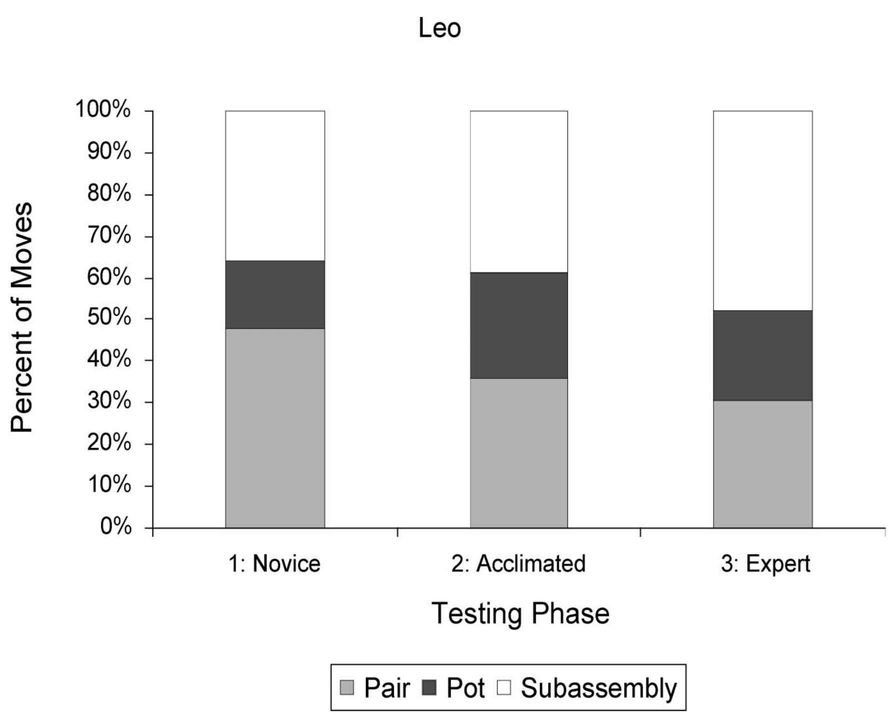


Figure 3. Percentage that each combinatorial procedure was used, based on the level of expertise in Experiment 1. An asterisk indicates that the monkey's use of the different combinatorial procedures was dependent on the level of experience, eight trials per phase; Leo, $\chi^2(2, N = 259) = 4.19$, $p = .38$; Nick, $\chi^2(2, N = 491) = 35.43$, $p < .05$.

Table 2
Residual Analysis for the Chi-Square Test of Independence for Nick in Experiment 1: Expertise

Phase	Procedure: Pair Residual	Pair p	Pot Residual	Pot p	Subassembly Residual	Subassembly p
Novice	14.82	.001	9.30	.005	0.00	.496
Acclimated	3.66	.029	1.36	.146	0.08	.370
Expert	4.14	.001	2.05	.010	0.02	.417

Note. Residual reflects the difference between observed and expected values.

trial, the more likely that a five-cup structure would eventually be constructed. Additionally, the more times a cup is moved per trial, the more opportunities there are to learn about the greater number of arm movements, and thus energy, required for potting as compared with subassembly. This could lead a more experienced monkey to use subassembly more often than potting.

As predicted by the dynamic systems approach, a dominant stable procedure emerged with experience. As novices in Testing Phase 1, Nick showed a preference for pairing, tied with subassembly, whereas Leo did not have a preference for a particular strategy. This demonstrates that the attractor landscape is not well formed (for Leo), and if there is an attractor basin, it is not necessarily leading toward the most efficient of the combinatorial procedures (as in Nick's case). On the basis of the baseline combinatorial activity (during the first eight training trials with 3 cups), the monkeys did not initially engage in a large amount of combinatorial activity. The few combinatorial attempts that they made were primarily pairing. The monkeys' increased use of both the subassembly and pot procedures, as compared with the simpler pairing procedure, with added experience demonstrates that there is a microdevelopmental sequence that mimics the progression observed cross-sectionally in children (Greenfield et al., 1972; see also Johnson-Pynn et al., 1999). That is, the monkeys changed from using a large amount of pairing to completing structures with more elements.

Experiment 2: Task Demands

Method

Subjects

Six male capuchin monkeys between 7 and 13 years old participated: Nick (7 years old), Leo (7 years old), Chris (8 years old), Xenon (10 years old), Jobe (10 years old), and Xavier (13 years old). Food and housing conditions were the same as in Experiment 1.

Apparatus

The same variable-sized and same-sized cups, testing cages, and video recording equipment as in Experiment 1 were used.

Procedure

Training. All monkeys had experience with manipulating nesting cups prior to the beginning of this experiment: Nick and Leo had completed Experiment 1, and the other 4 monkeys were previously trained to combine the variable-sized cups (Johnson-Pynn et al., 1999) by using a similar procedure to Experiment 1, except that they were trained with only the variable-sized cups instead of the same-sized cups. To equate the monkeys' training experience, these 4 monkeys were trained to combine the same-sized cups into stable structures without bias for how the stable structure was formed, as Nick and Leo had already achieved in Experiment 1. As in the initial training, training began with a single cup. After the cup was returned to the experimenter six consecutive times, two cups were provided. When criterion was reached for each number of cups, an additional cup was added until the monkey was able to successfully combine five same-sized cups into a stable structure. For all trials in which a structure was successfully constructed, a piece of dried fruit or cereal was given as a reward.

Nick and Leo had previously learned to combine the same-sized cups in Experiment 1. They demonstrated that they were still at criterion for placing five same-sized cups into a stable structure before proceeding to the testing phase.

Testing. All 6 monkeys were given eight testing trials with the same-sized cups. Testing followed the same procedures as in Experiment 1, except that five same-sized cups were used.

Scoring and Analysis

As in Experiment 1, we scored the procedure used for each combinatorial move and the number of five-cup stable structures. These variables were compared with the performance with the variable-sized cups. For Nick and Leo, the data from Experiment 1, Test Phase 2, were used to describe their performance with the variable-sized cups. Data from Test Phase 2 were selected as the comparison because it was effectively the monkeys' first test sessions with the variable-sized cups in which they routinely created multicup structures. Data from Johnson-Pynn et al. (1999) were used for the other 4 monkeys to describe their performance with the variable-sized cups. For each type of object, eight pairs (the first move from each trial) were subtracted from the data because these did not reflect the combinatorial choices of the monkey.

Across individuals, Wilcoxon signed-ranks test were used to determine, overall, (a) whether the monkeys used more moves per testing phase with the variable-sized cups than with the same-sized cups and (b) whether they were able to complete more five-cup structures with the same-sized cups than with the variable-sized cups. Wilcoxon signed-ranks test were used because of the heterogeneity of variance between the groups, which violated an assumption of the t test.

Chi-square goodness-of-fit tests were used to determine whether each monkey had a preference for a particular procedure for each type of cup. Using 2×3 chi-square tests of independence, we compared the pattern of procedure preferences for each individual across the two types of cups. If differences were found, post hoc analysis was used to determine which procedure was used differentially with the two types of cups.

The number of significant post hoc analyses was weighed against the total number of post hoc comparisons with a binomial test, assuming that there would be a .05 chance for a spurious significant finding in each analysis. This determined the probability that the number of significant post hoc results in this experiment would have occurred by chance.

Results

All of the subjects constructed five-cup structures at least once with either the variable-sized or same-sized cups. They completed more five-cup structures with the same-sized cups than with the variable-size cups (M = 7.67 ± .21 and M = 3.67 ± 1.17, respectively; $z = 2.06$, $p < .05$), and they made fewer moves with the same-sized cups than with the variable-sized cups (M = 27.83 ± 1.18 and M = 240.00 ± 62.98, respectively; $z = -2.20$, $p < .05$; see Table 3).

Of the 6 monkeys, 4 did not use the three combinatorial procedures at chance levels with the variable-sized cups. Two monkeys used the pot procedure more frequently than pair or subassembly. One monkey used potting procedures the most frequently followed by pair, which it used more often than subassembly, and the last monkey primarily used both pairing and potting more as compared with subassembly (see Table 4).

In contrast, all 6 of the monkeys showed a preference for a specific combinatorial procedure with the same-sized cups. Both Nick and Leo used more subassembly than potting or pairing. These 2 monkeys potted and paired at the same rate. Xenon did the opposite, using the pot procedure more often than either subassembly or pair, and used subassembly and pair at the same rate. Chris and Xavier used pot and subassembly at the same rate with the same-sized cups, and they used both subassembly and pot more than pairing. Jobe used the pot procedure more often than subassembly or the pair procedure, which were each used at the same rate (see Table 4).

Nick, Leo, Chris, and Xavier showed a significant change in procedure selection depending on the type of cup that was being manipulated (see Figure 4). Nick and Leo increased their proportional use of subassembly and decreased their potting when using the same-sized cups: Nick, $\chi^2(1, N = 91) = 12.35$, $p < .05$; Leo, $\chi^2(1, N = 73) = 4.24$, $p < .05$. Xavier increased proportionally the use of subassembly to a greater degree (from 10% to 30%) than he increased potting (from 47% to 61%) when using the same-sized cups versus the variable-sized cups, $\chi^2(1, N = 119) = 4.02$, $p < .05$. All 4 individuals that changed the pattern of procedure use on the basis of the type of object to be combined proportionally used more subassembly and less pairing when they were manipulating the same sized cups: Nick, $\chi^2(1, N = 94) = 13.67$; Leo, $\chi^2(1, N = 83) = 5.14$; Chris, $\chi^2(1, N = 154) = 5.35$; and Xavier, $\chi^2(1, N = 94) = 21.66$; $ps < .05$. Only Xavier showed a change in the use of pair and pot on the basis of the type of cup. He used potting proportionally more often and pairing less often with the same-sized cups as compared with the variable-sized cups, $\chi^2(1, N = 161) = 10.43$, $p < .05$ (see Figure 4). On the basis of the binomial probability of obtaining 31 out of 42 significant post hoc findings ($p = 1.13 \times 10^{-31}$), there were more significant results than would be expected by chance.

Table 3
Comparison of Manipulating Variable-Sized and Same-Sized Cups in Experiment 2

Monkey	No. of moves	No. of 5-cup structures
	Variable size	
Nick	95	3
Leo	75	3
Chris	344	8
Xenon	320	6
Jobe	454	2
Xavier	152	0
$M \pm SEM$	240.00 ± 62.98*	3.67 ± 1.17*
	Same size	
Nick	24	8
Leo	31	8
Chris	25	8
Xenon	26	8
Jobe	26	7
Xavier	35	7
$M \pm SEM$	27.33 ± 1.74	7.67 ± 0.21

Note. No. of moves = the mean (± *SEM*) number of moves per testing phase; No. of 5-cup structures = the mean (± *SEM*) number of trials ending in the construction of a five-cup structure per testing phase.
* Indicates a significant difference between the two types of cups ($p < .05$) based on paired t tests.

Table 4
Number of Moves of Each Combinatorial Procedure Exhibited by Each Monkey in Experiment 2: Task Demands

Monkey	Type of Cup	Procedure			Total (N)	$\chi^2(2)$
		Pair	Pot	Subassembly		
Nick	Variable	28	25	42	95	5.20
	Same	0	0	24[a]	24	55.85
Leo	Variable	27	19	29	75	2.24
	Same	6	4	21[a]	31	16.71
Chris	Variable	73	202[a]	69	344	99.84
	Same	2	13[a]	10[a]	25	7.76
Xenon	Variable	74	156[a]	90	320	35.43
	Same	3	18[a]	5	26	15.31
Jobe	Variable	123	248[a]	83	454	97.91
	Same	6	18[a]	2	26	16.00
Xavier	Variable	65[a]	72[a]	15	152	38.14
	Same	3	21[a]	11[a]	35	13.94

[a] Indicates the procedure used the most frequently ($p < .05$) based on a chi-square test, where $df = 1$. If two procedures are marked, they are used at the same rate, but more often than the remaining procedure.

Discussion

This experiment showed that the characteristics of the objects being combined and individual preferences influenced the procedures the monkeys used to create nested structures. This experiment produced three important results: First, the variable-sized cups were more difficult for the monkeys to combine into five-cup structures than the same-sized cups as evidenced by the smaller number of five-cup structures completed and the greater number of moves per testing series. Seriation is a more difficult task than nesting. When objects must be placed in a specific order, there is the potential for order mistakes to occur. Even if an individual had a strong preference for a particular procedure, unless it seriated the cups perfectly on the first attempt, it might have to shift procedures to fix a mistake in the structure. Second, for both types of cups, some individuals used one procedure more than the others. This indicates that the monkeys were not randomly using the combinatorial procedures. Finally, the procedure used less often (between

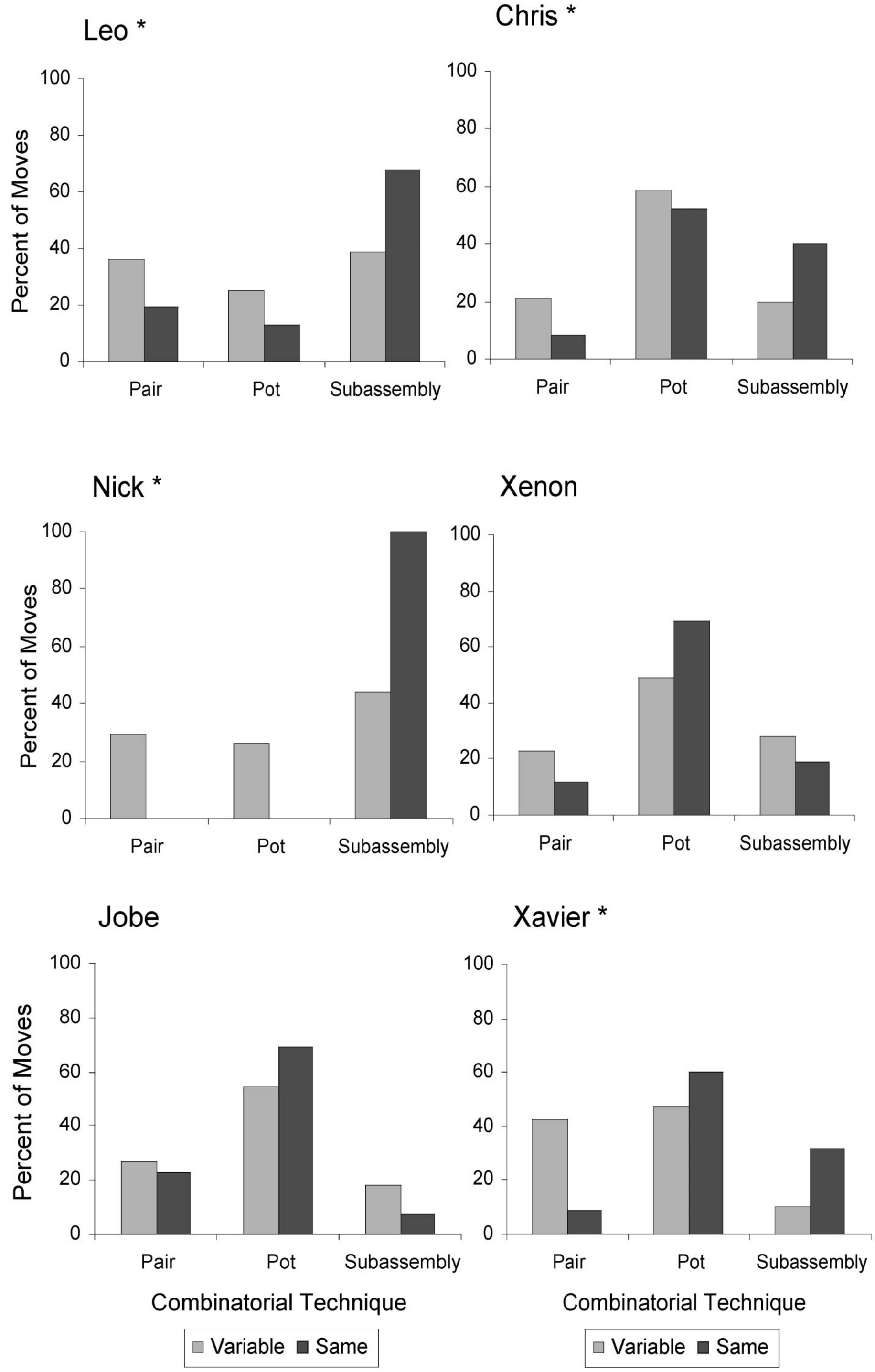


Figure 4. Percentage that each combinatorial procedure was used, based on the type of cup manipulated. An asterisk indicates that the monkey's use of the different combinatorial procedures was dependent on the type of cup being manipulated (all $ps < .05$): Leo, $\chi^2(2, N = 106) = 7.45$; Nick, $\chi^2(2, N = 199) = 24.14$; Chris, $\chi^2(2, N = 369) = 6.51$; Xavier, $\chi^2(2, N = 187) = 19.87$.

pot and subassembly) decreased in relative frequency for 4 of the 6 individuals, and the more frequently used procedure increased for 5 out of the 6 monkeys when tested on the same-sized cups as compared with the variable-sized cups (see Figure 4).

These findings are in accord with the predictions drawn from dynamic systems theory. In the language of dynamic systems theory, the attractor landscape for these two objects was different for some individuals. For these individuals, the pair basin became shallower whereas the attractor basin associated with either pot or subassembly broadened and became deeper, depending on the particular behavior that was previously used more often. The different types of cups did not cause the monkeys to shift between their dominant procedures. Rather, it caused the most used procedure (either pot or subassembly) of 4 of the 6 monkeys to be expressed at a greater rate while manipulating the same-sized cups as compared with the variable-sized cups.

It may also be that the constant size of the nested sets of the same-sized cup structures also facilitated the monkeys' treatment of the sets as a single unit and promoted subassembly, compared with the variable-sized cups, for which the appearance of the set is relatively less consistent. This would promote increased use of subassembly with same-sized cups compared with variable-sized cups, as we observed. Both haptic and visual properties support the observed outcome.

Experiment 3: Subassembly Training

Method

Subjects and Housing

Two monkeys, Chris and Xenon, participated in this experiment. These monkeys previously demonstrated a preference for the pot procedure to create stable structures with variable-sized cups (Johnson-Pynn et al., 1999). Housing and care were the same as in Experiment 1.

Apparatus

Subjects were trained and tested in the same testing cages and with the same variable-sized cups as in Experiment 1. All testing trials were recorded on videotape.

Procedure

Training. The 2 monkeys were explicitly trained to complete a four-cup structure by using subassembly with variable-sized cups. A four-cup structure was used as opposed to the five-cup structures from the previous experiments because the four-cup structure did not have to be broken apart to be returned to the experimenter through the opening in the door. Each training trial began with the presentation of the two smallest of the variable-sized cups. When these two cups were successfully paired, a third, larger cup was presented. If the cups were combined using the subassembly procedure, the largest of the four cups was presented. If the structure was completed using a subassembly procedure, the monkey was rewarded. If at any point after pairing the initial two cups the monkey used any procedure other than subassembly, that training trial was ended without a reward by the experimenter asking for all of the cups. The two criteria for learning to preferentially use subassembly were (a) six consecutive four-cup structures created with one pair move and two subassembly moves and (b) one pair move and two subassembly moves on a probe trial in which the cups were presented in the opposite order (largest to smallest).

Testing. Chris and Xenon were given eight testing trials by using the same procedure as in Experiment 1, Testing Phase 1.

Scoring and Analysis

After scoring each move as pair, pot, or subassembly and the number of five-cup structures, one pairing move was subtracted for each trial. The distribution of individual procedure preference in these trials was compared with the pattern previously exhibited (Johnson-Pynn et al., 1999) with the variable-sized cups prior to subassembly training by using 2 × 3 chi-square tests for independence. The number of moves per phase was compared for each individual by using chi-square goodness-of-fit tests.

The number of significant post hoc analyses was weighed against the total number of post hoc comparisons with a binomial test, assuming that there would be a .05 chance for a spurious significant finding in each analysis. This determined the probability that the number of significant post hoc results in this experiment would have occurred by chance.

Results

Both monkeys quickly reached criterion for subassembly training. Chris reached this point after 36 trials, and Xenon required only 12 trials. After subassembly training, Xenon created seven five-cup structures as compared with eight prior to this training. Chris constructed six five-cup structures initially, followed by eight completely seriated structures after subassembly training. Both Chris and Xenon used fewer moves per testing phase after subassembly training than before this training procedure: Chris, $\chi^2(1, N = 471) = 109.34$, $p < .05$; Xenon, $\chi^2(1, N = 508) = 39.24$, $p < .05$ (see Table 5). Chris decreased his total number of moves by 65% whereas Xenon reduced his total number of moves by 44%.

After subassembly training, Xenon used the three procedures at different frequencies, using subassembly at significantly greater rates than either pot or pair and using pair and pot at the same rate. Chris also showed a significant preference for subassembly over potting. Pairing was used at a rate that was intermediate between

Table 5
Number of Moves of Each Combinatorial Procedure Exhibited by Chris and Xenon in Experiment 3: Subassembly Training, Compared With Their Original Performance (Reported in Johnson-Pynn et al., 1999)

Training	Procedure: Pair	Pot	Subassembly	Total (N)	$\chi^2(2)$
		Chris			
Original	73	202[a]	69	344	99.84
Subassembly	48[a]	27	52[a]	127	7.88
		Xenon			
Original	74	156[a]	90	320	35.43
Subassembly	64	44	80[a]	188	11.20

[a] Indicates the procedure used most frequently ($p < .05$) based on a chi-square test, where $df = 1$. If two procedures are marked, they are used at the same rate, but more than the remaining procedure.

subassembly and potting, although it was not significantly different from either of these other procedures (see Table 5).

On the basis of a 3 × 2 chi-square test of independence, the monkeys differed in the way they combined the objects before and after the training to use subassembly: Chris, $\chi^2(2, N = 471) = 47.68$; Xenon, $\chi^2(2, N = 508) = 28.86$; $p\text{s} < .05$ (see Figure 5). Specifically, for both monkeys, after training to use subassembly, the relative use of subassembly increased while potting decreased: Chris, $\chi^2(1, N = 350) = 40.32$; Xenon, $\chi^2(1, N = 370) = 24.75$; $p\text{s} < .05$ (see Figure 5). The binomial probability of obtaining 31 out of 42 significant post hoc findings ($p = 1.57 \times 10^{-8}$) indicates that there are more significant results than would be expected by chance.

Discussion

The nature of prior experience with combining cups affects the manner in which the monkeys combined cups into structures. The short training in subassembly procedures used in the experiment was sufficient to change the response trajectory such that both individuals reduced potting and increased the relative frequency with which they used the subassembly procedure. This is similar to the effects of brief training on the hierarchical planning abilities of children with language impairments (Kamhi & Ward, 1995). These children were tested to determine their ability to construct complex straw structures by using a sequential procedure. The children who initially were unable to complete this task were able to use the sequential procedure when given verbal and nonverbal feedback and were able to adopt this hierarchical procedure within 10 trials. Like the monkeys, the children were able to engage in complex hierarchical behavior after brief instruction.

Although subassembly is motorically more efficient than the other types of moves, unless planning occurs, there is no reason why it would reduce the total number of moves in a testing phase. However, this is what occurred. It might be that in learning to use subassembly, the monkeys also learned to plan better or order the cups better. Both of these factors could lead to an increase in subassembly with development. Additionally, the subassembly training procedure may have changed the type of errors that the monkeys made while combining the cups. There can be errors due to incorrect placement (the monkey attempts to nest a large cup inside of a smaller cup) or due to an incorrect order (the monkey correctly nests a smaller cup into a larger cup, creating a stable structure, but the cups are not adjacent to each other in sequence). Additional analyses will be made in the future to determine if the type of errors changed after subassembly training.

General Discussion

These findings viewed together change the way combinatorial manipulation of cups can be interpreted. In all three experiments, altering the context and the experience of the individual altered the monkeys' combinatorial behavior. If there were a central conceptual limitation on the procedures an individual could use to seriate cups (as suggested by Greenfield et al., 1972), it would not be possible to switch to a new dominant procedure in a minimal time period as 2 monkeys did. Experience could also possibly enable the developmental shift toward the pot and then subassembly procedures seen in children, rather than a qualitative change in how children organize their behavior. Because experience alone, as in Experiment 1, did not reduce the number of moves required to seriate the cups, but specific subassembly training did cause the monkeys to seriate the cups by using fewer moves, there is a possibility that there is a qualitative change in combinatorial behavior associated with subassembly training. It is possible that the monkeys learned to produce the correct order during the subassembly training. However, considering the relatively few trials required to teach the monkeys to use subassembly when combining cups as compared with their lengthy initial training to combine the cups in the first place, it is more likely that subassembly in some way facilitated more efficient seriation. Perhaps the hierarchical nature of the subassembly procedure enhanced perception of the hierarchical nature of the nesting cups, causing the monkeys to attend to size differences in a different manner than they had previously. Alternatively, perhaps they became better at correcting mistakes. One strategy that the monkeys may have been using to detect mistakes was a "wiggle strategy." Cups that were in the correct position fit together tightly, whereas cups that were incorrectly placed had a looser fit. Only the incorrect placement wiggled when the stack was moved.

Dynamic systems theory accounts not only for the findings in this particular set of experiments but for the transitions between combinatorial procedures in children as well. As children mature, they encounter more situations in which objects are combined. Each time this occurs, it will lead to the ongoing modification of the attractor landscape. As in Experiment 1, added experience will lead to expertise. Just as expert walkers develop a stable gait (Clark & Phillips, 1993), so too will expert stackers develop a stable pattern of combinatorial activity.

It is likely that children would also show a change in procedure on the basis of the affordances of the objects (Lockman, 2004; Ruff, 1984). This leads to the prediction that children would progress through the different procedures at an earlier age with objects that are easier to combine, such as the same-sized cups used in Experiment 2. There are fewer factors influencing the combination of same-sized cups, so an attractor basin may become deep and stable more quickly.

As shown in Experiment 3, when one procedure is a better choice than the other procedures of combination in terms of reducing effort, monkeys shifted their behavior to reflect that situation. The specific reward structure can be viewed as scaffolding, making the inherent efficiency benefits of subassembly more salient to the monkey. This resulted in a microdevelopmental push toward the typical behavior observed in older human children and adults. This type of transition to a higher than expected developmental state is easily explained (i.e., predominant use of subassembly to seriate cups; Greenfield et al., 1972) by a dynamic system in which a change in any one variable can alter behavioral outcomes. In the future, in both humans and nonhuman primates, other factors that can elicit these shifts could be investigated. If, for example, the distance between the cups to be combined were greater, the difference in the motor efficiency between pairing, potting, and subassembly would be more pronounced and could lead to the same microdevelopmental improvement with fairly limited practice.

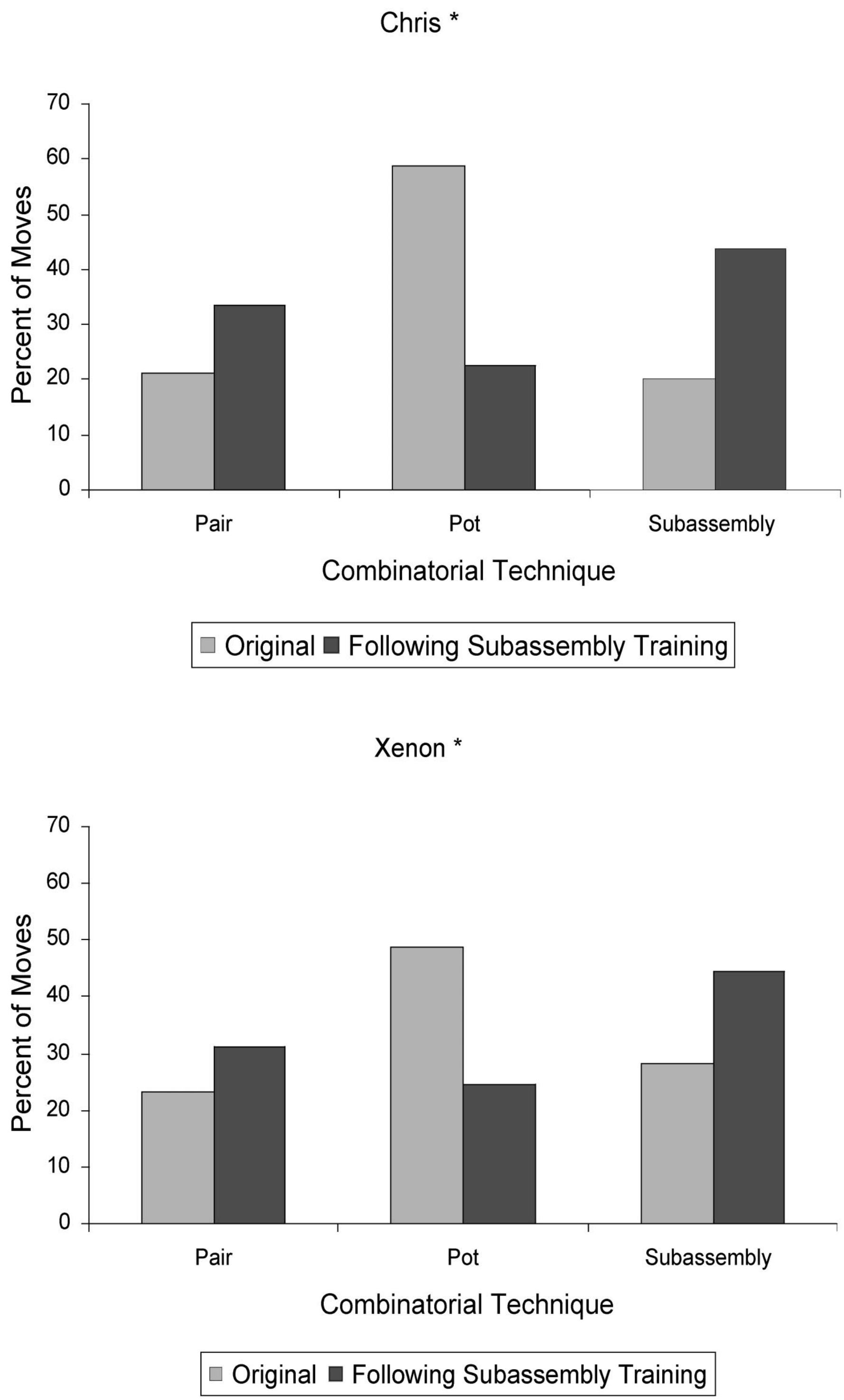


Figure 5. Percentage that each combinatorial procedure was used, based on the type of training history. An asterisk indicates that the monkey's use of the different combinatorial procedures was dependent on the type of cup being manipulated (all $ps < .05$): Chris, $\chi^2(2, N = 471) = 47.68$; Xenon, $\chi^2(2, N = 508) = 28.86$.

The focus of this study was specifically to look at the possibility that changes in performance in capuchins could be accounted for by a dynamic explanation. The dynamic perspective is particularly useful for studying the way behavior changes as a result of multiple factors. In contrast, Johnson-Pynn et al. (1999) focused on the overall pattern of combinatorial actions in different species. The results of these two studies and their interpretation are not in conflict with one another; they focus on different aspects of performance. The current findings extend the findings of Johnson-Pynn et al. (1999) in that they demonstrate how sensitive the combinatorial actions of monkeys can be to the context of activity (in this case, the shape and size of cups). Casting the results in a dynamic systems perspective permits interesting predictions about developmental and microgenetic processes affecting combinatorial activity across species.

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