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Techniques, Demands and Success in Structure Construction in Tufted Capuchin Monkeys (*Cebus apella*)

(Under the Direction of DOROTHY M. FRAGASZY)

Previous research on children has revealed three strategies used to combine nesting cups into stable seriated structures. These techniques may differ in cognitive complexity with the putatively most advanced of these emerging as the dominant strategy at about age three. Six monkeys' (*Cebus apella*) combinatorial strategies and successes at the same tasks presented to children were evaluated. The current study examined a) if unguided experience is sufficient to result in a shift by the monkeys towards the more advanced methods, b) if the techniques used are dependent on the type of object combined, and c) if strategy selection can be altered by specific training history. Some monkeys showed a preference for the putatively most complex technique. All three environmental and experiential factors produced a change in strategy selection for some individuals, suggesting that combinatorial strategy is a product of the dynamic influences of innate tendencies, environmental circumstances and prior experiences.

INDEX WORDS: Seriation, Monkeys, Dynamic systems

TECHNIQUES, DEMANDS AND SUCCESS IN STRUCTURE CONSTRUCTION IN TUFTED CAPUCHIN MONKEYS (*CEBUS APPELLA*)

by

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B.S., Tufts University, 1995

A Thesis Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2001

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ACKNOWLEDGEMENTS

I would like to thank Dr, Dorothy Fragaszy for her support and scholarly guidance with this project. I am also grateful to Dr Irwin Bernstein and Dr. Carolyn Ehardt for their editorial contributions.

I also wish to acknowledge Aeneas C. Murnane for his assistance with administering the procedure and Dr. Julie Johnson-Pynn for her intellectual inspiration.

Supported by Grant HD06016 to Georgia State University.

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INTRODUCTION

When an individual manipulates objects, there is the opportunity for rules to guide this manual activity. Rules allow the individual 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 et al., 1972). Three main combinatorial strategies (Figure 1) were identified by Greenfield et al.(1972). The simplest strategy is the "pair," where nesting or stacking combines one cup with another. The more complex "pot" method requires two or more cups to be combined with another cup such that only the single cup is the active unit. In potting, one cup is placed inside of two or more cups. The most complex "subassembly" strategy occurs when two or more cups become a subunit and are combined with one or more of other cups. With this method the subunit is transformed from the acted-upon object to the active object. The subunit consists of two or more cups. When the subunit was originally made one of the cups was an active object, while the other one was a receiving object. The key aspect of subassembly is that the role of an item that was once a receiving object is transformed into an active object and that the multi-cup structure now functions as a single item. Greenfield et al. (1972) considered this method the most complex because it requires a hierarchical combination of multiple cups. These strategies occur in children in a sequential order with the pair strategy dominant at 11 months, the pot strategy at 20 months and the subassembly strategy emerging as dominant at 36 months. Greenfield

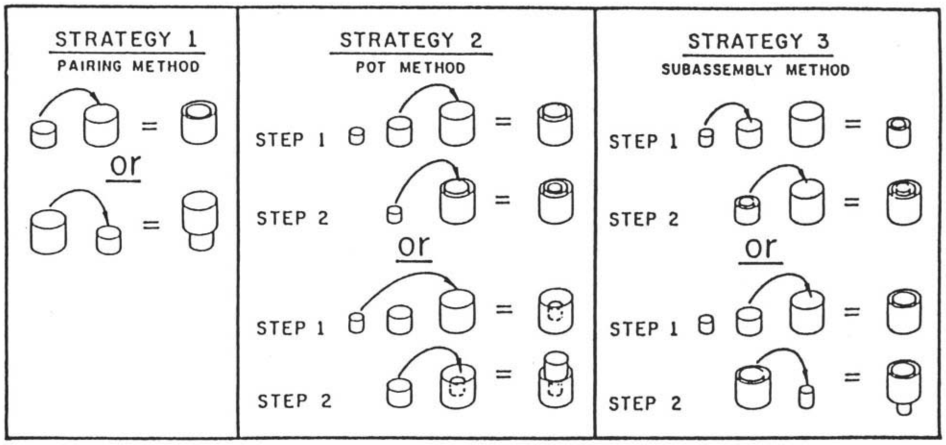


Figure 1. Strategies used for combining cups as identified by Greenfield, Nelson and Saltzman, 1972.

(1991; Greenfield et al. 1972) suggests that this developmental sequence is not only correlated with the development of language, but that it is controlled by the same underlying mechanism. Language, also, progresses from combinations of two words (pair), to sentences with multiple, parallel phrases (pot), and then sentences with multiple phrases joined based on their relation to one another (subassembly).

Combinatorial manipulation has been tested in non-human primates with varying results (Matsuzawa, 1991; Westergaard, 1992,1993 and 1999;Westergaard & Suomi, 1994). Johnson-Pynn et al. (1999) investigated the strategies used to combine seriated cups by chimpanzees (*Pan troglodytes*), bonobos (*Pan paniscus*) and capuchins (*Cebus apella*). They found that all three species were able to create a seriated five-cup structure with variable-sized nesting cups. Not only did all three species display all of the combinatorial strategies that had been previously identified in humans, but there was no difference between the species in the techniques that they used to complete the task. Even when the language-trained apes in this study were looked at separately from the rest of the subjects, they demonstrated the supposedly more advanced subassembly technique at the same rate as the other apes and monkeys, contrary to previous findings (Matsuzawa, 1991) where an adult chimpanzee with language training showed a preference for subassembly.

Non-human primates, both with and without language training, perform the same on this task and some do so in a manner similar to linguistic humans. Therefore, it is unnecessary to suggest that the same mechanism that controls the hierarchical combinations of words into sentences is also responsible for manner in which objects are combined into structures. Perhaps the cognitive representational perspective is not the most useful here.

Since language ability does not appear to be necessary for the developmental progression in object combination, what then explains the existence of preferred strategies and the transitions between these preferences? As an alternative, rather than looking at the strategies as a stable characteristic of the individual's way of dealing with the task, the way that objects are combined can be viewed as a dynamic interaction between the natural tendencies of the individual, the result of past experiences and the demands of the objects themselves. This view has been labeled "dynamic systems" (Thelen and Smith, 1994). From a dynamic systems perspective, goal-directed actions are the product of movements with many degrees of freedom and changes in any one of these degrees of freedom can impact the resulting behavior. Only a limited number of actions will be elicited from all of the possible combinations of influences because multiple influences (within a given range) will result in the same behavioral outcome and because biomechanical constraints rule out some variations. This idea is similar to the way a ball will fall to the bottom of a valley regardless of the specific type of force applied to it at the peak. A wide range of environmental factors will lead to the use of only a small number of different responses.

Continuing the analogy where a ball falls down a slope, all possible behavioral outcomes of a given task can be viewed as a landscape with multiple valleys. 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 system develops, there is also bifurcation, where a single attractor splits into two behavior outcomes. With expertise in an area, an individual can detect important environmental distinctions and respond differentially in a situation-appropriate manner (Thelen and Smith, 1994).

An attractor landscape describing the combination of cups into stable structures would feature pair, pot and subassembly attractor basins. As each method is used there is a greater likelihood that it would 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. But in humans, there are opportunities for learning about combining objects in many typical activities such as when the child plays with his or her own set of nesting cups, plays with blocks or has a pretend tea party.

This model predicts that each individual would be expected to develop a strategy preference, but it would not explain the transition between the stages. Transitions could be understood to reflect the actor's growing ability to detect the efficiency of each technique. Pairing is the least efficient because it is impossible for a stable structure with more than two cups to be created using solely this technique. With potting and subassembly, both methods could result in a multi-cup stable structure, however they differ in efficiency of movement. If a paired structure is moved as a subunit to the next object to be combined an individual simply moves the stack of cups in a single motion to the next object. In comparison, with potting, the individual must first reach for the new object to be combined and then return that object to the working stack of cups. This results in twice as many body movements per combinatorial action when using the pot method as compared to the subassembly technique.

An efficiency model alone, however, cannot fully explain combinatorial behavior as it has been observed in human and non-human primates. An efficiency model would predict an initial stage where individuals have no strategy preference before the relative strengths of each strategy could be learned. Even in the first eight trials with variable-sized cups, monkeys, apes and children show preference for certain techniques (Greenfield et al., 1972 and Johnson-Pynn et al., 1999). The dynamic systems theory would account for this initial technique preference based on intrinsic characteristics of the individual, which is based on biological constraints and all prior experiences.

The purpose of this study was to explore the alternative offered by a dynamic systems theory explanation of the development of seriation. I did this by determining how aspects of combinatorial activity are controlled by in tufted capuchin monkeys: individual propensities, the characteristics of the object, and prior experience.

Based on a dynamic systems perspective, with more experience a preferred strategy should emerge and it should be the most efficient of the combinatorial techniques, subassembly. While the less efficient strategies should decrease, they will not disappear entirely unless the individual is able to seriate the cups without a sequence error. The preferred strategy will not always be the most appropriate one for fixing a mistake in the order of the cups. As each cup is moved, based on the structures already constructed, the particular characteristics of that situation will determine which combinatorial technique is best suited for each move. Experiment 1 looks at the way the monkey's success and combinatorial strategy changes with experience. It is expected that the monkeys will get better at the task 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) and not the number of moves required to construct that structure, since seriation can be achieved by trial and error combination of the cups and does not require the monkey to understand the ordinal relations of the objects. It is also predicted that, as experience increases, the monkeys will rely less on the pair strategy relative to the more efficient pot and subassembly techniques and that, as experts, the dominant strategy should be subassembly.

Previous research has used variable-sized cups to probe the development of combinatorial behavior. While 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 strategy 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 using all of the previously identified techniques. 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 to create structures with the same-sized cups. With the variable-sized cups, there is a chance that the individual would make an error, placing a cup in the wrong order, requiring an adjustment of the object and possibly prompting a shift in strategy. In dynamic systems terms, an error creates new circumstances that can result in a shift towards a different attractor basin, thus provoking a shift in behavior. The easier task would not provoke a shift in technique, resulting in a stronger preference for a specific method of combinatorial behavior. Of the two techniques that will allow the creation of structures with more than two objects (pot and subassembly), the monkey should not change the order of strategy preference depending on the type of cup. Thus, I predict a difference between outcomes in Experiment 1 (with variable-sized cups) and Experiment 2 (same-sized cups). In Experiment 1, I predict a shift in strategies with experience. In Experiment 2, I predict that the distribution of strategies will not change and thus will differ from Experiment 1.

In Experiment 3, the monkey is given specific training in the subassembly technique. Dynamic systems theory would say that this experience would strengthen the attractor basin for subassembly and lead to a greater use of the method in the future. Based on this, I predicted that the monkeys would shift their preferred strategy towards a preference for subassembly after this training. This would demonstrate that the method used to combine cups reflects recent experience rather than a pre-existing central cognitive strategy.

EXPERIMENT 1: EXPERTISE

Method

Subjects and Housing

The subjects in this experiment were two, young adult, male capuchin monkeys (*Cebus apella*), Nick and Leo, both 7 years old. These monkeys were housed as a pair in indoor cages at the University of Georgia. Their home cage was 181 x 137 x 71 cm. 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. The height of each cup was 5 cm with a 5 cm diameter and any cup could be nested into any other cup (Figure 2). The second set of cups were plastic children's 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 cm to 5 cm, and in diameter from 5 cm to 7.5 cm. These cups could only fit together in one order. The third smallest cup of these six was not used. (Figure 3).

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

Figure 2. A set of stainless steel same-sized cups

Figure 3. A set of plastic variable-sized cups

All testing trials were recorded on VHS tapes using a Panasonic video camera (model WV-CL700) facing the front of the testing cage.

Procedure

Training Phase 1. Each subject was initially trained to combine cups to form a single stable structure. Both monkeys were trained with the same-sized cups (Figure 4). They were first taught to give a single cup back to experimenter. They were then given two of the same-sized cups and rewarded for creating a two-cup structure. 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. 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 technique used to create that structure

Test Phase 1- Novice. After completing training, each subject was given eight trials with the variable-sized cups. Five of the cups were given to the monkeys for them to manipulate. The third smallest cup, of the original six, was not included in this testing series. Each test trial was approximately three minutes. If, however, the subject was still working at the end of the trial, additional time was allowed. A trial ended with the completion of a five-cup structure or when the subject finished with 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.

<u>Figure 4.</u> A tufted capuchin monkey (*Cebus apella*) manipulating same-sized cups.

Training Phase 2. Nick and Leo were provided additional exposure to the variable-sized cups in this phase to allow familiarity with the variable-sized objects (Figure 5). Familiarity was determined based on the subject's ability to combine two of the variable sized cups by pairing, demonstrating the ability to correctly align the cups, in six consecutive attempts. Nick required additional training following his first exposure to the nesting cups. He was given two, randomly selected, variable size cups at a time until he was able to pair them successfully six consecutive times. The other subject Leo did not require this additional training.

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 is defined as at creating a seriated, variable sized,five-sup structure on six consecutive trials. Randomly selected variable-sized cups were presented. First two cups were given. After they reached criterion with combining the two cups, six consecutive successes, three cups were presented. Additional cups were added after criterion was reached at each level until the monkeys were able to combine five variable-sized cups to create a single stable structure utilizing all available cups.

Testing Phase 3-Expert. Nick and Leo were again tested using the same procedure as in Testing Phase 1.

Scoring and Analysis

All testing trials were scored using The Observer for Windows (Noldus, Wageningen, The Netherlands). For each testing trial, the strategies used in combining

Figure 5. A tufted capuchin monkey (*Cebus apella*) manipulating variable-sized cups.

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). Each time a stable structure was created, the numbers of cups in all structures were recorded. Since, by definition, the first move could only be scored as a pair, because there were no multi-cup 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 was used to determine if each individual used the three strategies in a manner different from chance. If an individual showed a non-random pattern of strategy choice, post hoc analysis was done to determine the specific order of preference.

Test Phases 1, 2 and 3 were compared for both individuals using two 2x3 Chi-square tests of independence. If the pattern of strategy choice was different between phases, post hoc analysis was conducted to determine where those differences lay. The number of moves per phase was also compared for each individual 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.

Results

Both of the subjects were able to construct a variable-sized, five-cup seriated structure 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.

Nick and Leo both increased the total number of moves per testing phase with experience (χ^2 (2) = 396.37 and χ^2 (2) = 106.22 respectively, $p<.05$). Nick used 28 moves in phase 1, 95 combinations in phase 2 and 368 moves in phase 3. Leo used 25, 75 and 159 moves in these same phases.

Leo did not show a preference for any of the three identified strategies in testing phase 1 or 2 (χ^2 (2) =3.92 and 2.24 respectively, $p=.15$ and .32) but he used the strategies in a manner different from chance in testing phase 3 (χ^2 (2) =17.09, $p<.05$). In this phase he had a specific preference for subassembly over pairing and potting methods (χ^2 (1) = 14.97, $p< .05$), which were the same as each other (χ^2 (1) = 2.71, $p>.05$). (Table 1).

Nick used the combinatorial strategies in differing frequencies for testing phases 1 and 3 (χ^2 (2) =14.21 and 55.85, $p<.05$), but not in phase 2 (χ^2 (2) =5.20, $p<.07$). In phase 1, he showed a significant preference for subassembly over potting (χ^2 (1) =13.00, $p<.05$) and for pairing over potting (χ^2 (1) =15.00, $p<.05$) but no difference between subassembly and pairing (χ^2 (1) =0.14, $p=.71$). In phase 3, when Nick was considered an expert at combining cups, he used the potting method more than pairing (χ^2 (1)=32.65, $p<.05$), subassembly more than pairing (χ^2 (1) =56.50, $p<.05$) but did not use

Table 1.

<u>The number of moves of each combinatorial technique exhibited by Nick and Leo in Experiment 1: Expertise.</u>

		Strategy				
Monkey	Phase	Pair	Pot	Subassembly	Total	χ^2 (df=2)
Nick	Novice	15 *	0	13 *	28	14.21
	Acclimated	28	25	42	95	5.20
	Expert	58	138	172 *	368	55.58
Leo	Novice	12	4	9	25	3.92
	Acclimated	27	19	29	75	2.24
	Expert	49	34	76 *	159	17.09

"*" Indicates the strategy used the most frequently, $p<.05$, based on a $\chi^2(1)$ If two techniques are marked, they are used at the same rate, but more than the remaining method.

significantly more often use subassembly than potting (χ^2 (1) =3.73, p=.053; see Table 1).

The pattern of technique used differed depending on the level of experience for Nick (χ^2 (4) =35.43, p<.05) but not significantly for Leo (χ^2 (4) = 4.19, p=.38; see Figure 6). Based on residual analysis (Siegel & Castellan, 1988), pairing was used more than would have been expected based on performance at all levels of experience when Nick was a novice and acclimated, and he used less pairing as an expert. Potting was used less than expected as a novice and more than expected as an expert (see Table 2).

Based on the binomial probability of obtaining 11 out of 18 significant post hoc findings (p= 1.09×10^{-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 neither taught any seriation techniques nor rewarded for their usage. The initial training that the monkeys received was sufficient to let the monkeys perceive that the task was to create a structure utilizing 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 size-cups required greater precision of alignment in order 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, they could create a hierarchically organized structure, and this ability improved with experience.

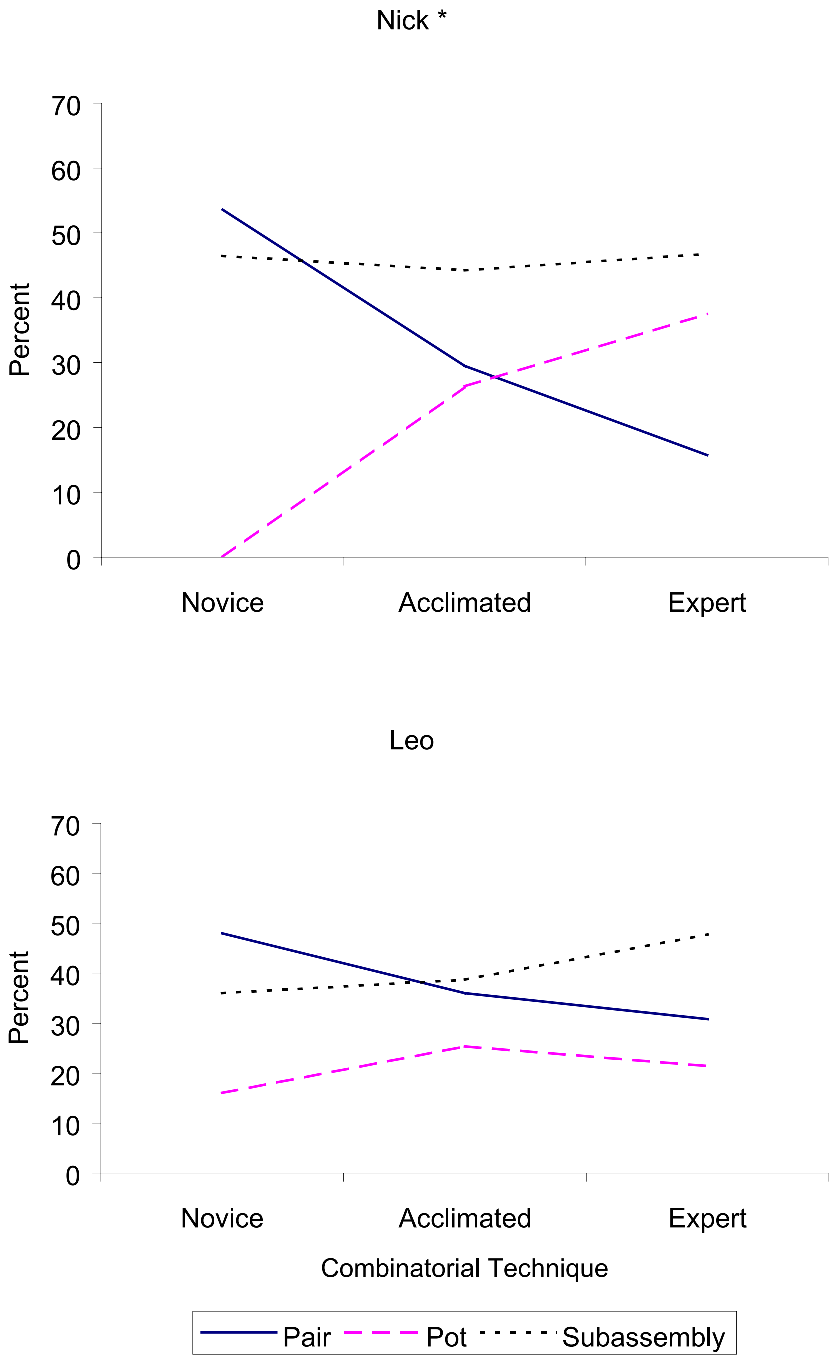


Figure 6. Percent each combinatorial strategy was used based on level of expertise. An * indicates that the monkey's use of the different combinatorial strategies was dependent on the type of cup being manipulated (Leo: $\chi^2(2) = 4.19$, Nick: $\chi^2(2) = 35.43$).

Table 2.

Residual analysis for the X^2 Test of Independence for Nick in Experiment 1: Expertise. Residual reflects the difference between observed and the expected values.

	Strategy					
Phase	Pair		Pot		Subassembly	
	Residual	p.	Residual	p.	Residual	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

Both of the monkeys increased the number of moves that they used in each testing series. If they were actually learning to seriate the objects better, there should be a decrease in total moves, but this is not the case. Rather, it appears experience taught perseverance. The monkeys were more attentive to the task and worked for longer periods on each trial before returning the cups to the experimenter to mark the end of the trial. Since trial and error combinations of the cups in varying orders could achieve success (a five-cup structure), the more moves per trial the more likely a five-cup structure would eventually be constructed.

As predicted by the dynamic systems approach, a dominant stable strategy emerged with experience. As novices in phase 1, Leo showed a preference for pairing while Nick did not have a preference. This demonstrates that the attractor landscape is not well formed, and if there is an attractor basin, it is not necessarily leading towards the most efficient of the combinatorial techniques. The increase in their use of the two more sophisticated subassembly and pot strategies, as compared to the simpler pairing technique, 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). Both individuals used more subassembly than would have been predicted based on Greenfield's theory that there is a link between hierarchical object manipulation and language. Since they do not use language, they would have been expected to use very little subassembly, if any.

EXPERIMENT 2: TASK DEMANDS

Method

Subjects and Housing

Six pair housed capuchin monkeys; Jobe (13 years old), Xavier (11 years old), Chris (9 years old), Xenon (11 years old), Nick (7 years old) and Leo (7 years old) were tested. 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. All other monkeys were previously trained to combine the variable-sized cups (Johnson-Pynn et al., 1999) using a similar procedure as in Experiment 1 except that they were trained only with the variable-sized cups instead of the same-sized cups.Four of the six monkeys were trained to combine the same-sized cups into stable structures. Nick and Leo did not require this training, as they were already proficient in manipulating the same-sized cups based on their training for 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 and additional cup was added until the monkey was able to successfully combine five same-sized cups into a stable structure. For all trials where 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 were tested, successfully, to ascertain that they were still at criterion for placing five same-sized cups into a stable structure before proceeding to the testing phase.

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

Scoring and Analysis

As in Experiment 1, each trial was scored on The Observer for the technique used for each combinatorial move and the number and size of each stable structure. This strategy selection behavior was compared to the performance with the variable-sized cups. For Nick and Leo their behavior from Experiment 1:Test Phase 2 was used to describe their performance with the variable-sized cups. Data from Johnson-Pynn et al. (1999) were used for Jobe, Xavier, Chris and Xenon 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, paired sample t-tests were used to determine if, overall, a) the monkeys used more moves per testing phase with the variable-sized cups, and b) if they were able to complete more five-cup structures with the same-sized cups. Chi-square goodness of fit tests were used to determine if each monkey had a preference for a particular strategy for each type of cup and if different numbers of moves were used between the two different types of cups. For each individual, using 2x3 Chi-square tests of independence, the pattern of strategy preferences were compared across the two types of cups. If differences were found, post hoc analysis was used to determine which technique was used differentially with the two types of cups.

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

Results

All of the subjects were able to construct 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 variable-size cups ($\underline{M} = 7.67 \pm .21$ and $\underline{M} = 3.67 \pm 1.17$ respectively; $\underline{t}(5)= 3.55$, $\underline{p}<.05$; see Figure 7). Each individual used fewer moves with the same-sized cups as compared with the variable sized cups (see Table 3) and there was an overall decrease in moves with the same-sized cups as compared to the variable sized cups ($\underline{M} = 27.83 \pm 1.18$ and $\underline{M} = 240.00 \pm 62.98$ respectively; paired $\underline{t}(5)= 3.33$, $\underline{p}<.05$; see Figure 8).

Four of the six (Chris, Xenon, Jobe, Xavier) monkeys did not use the three combinatorial strategies at chance levels with the variable sized cups. Chris and Xenon used the pot method more frequently than pair or subassembly. Jobe utilized potting methods the most frequently followed by pair, which was used more often than

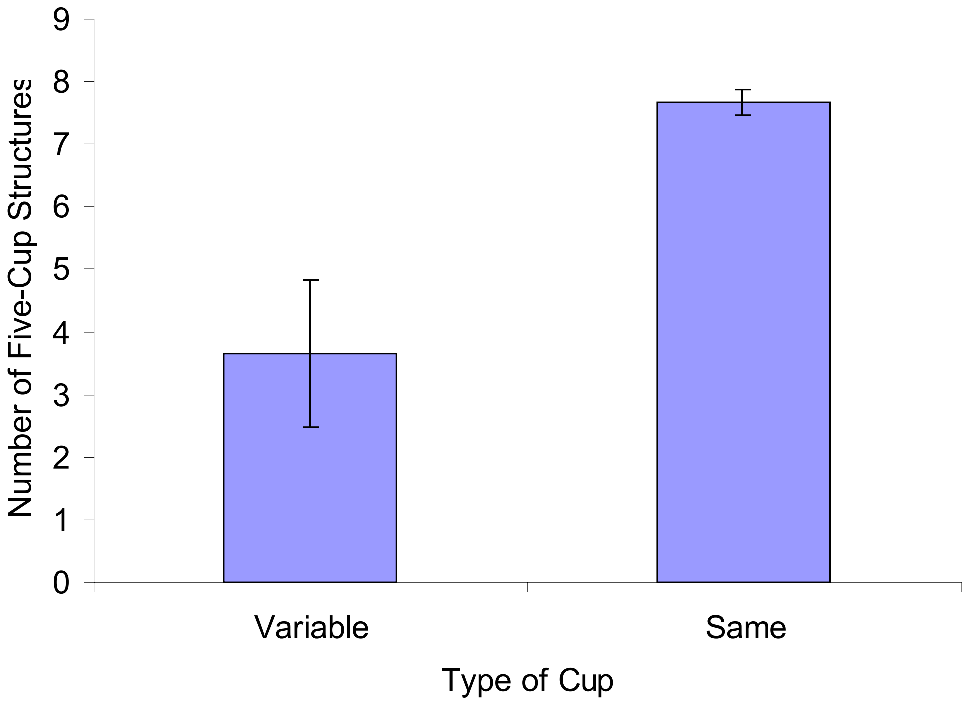


Figure 7. Mean number trials ending in the construction of a five-cup structure when manipulating variable-sized and same-sized cups.

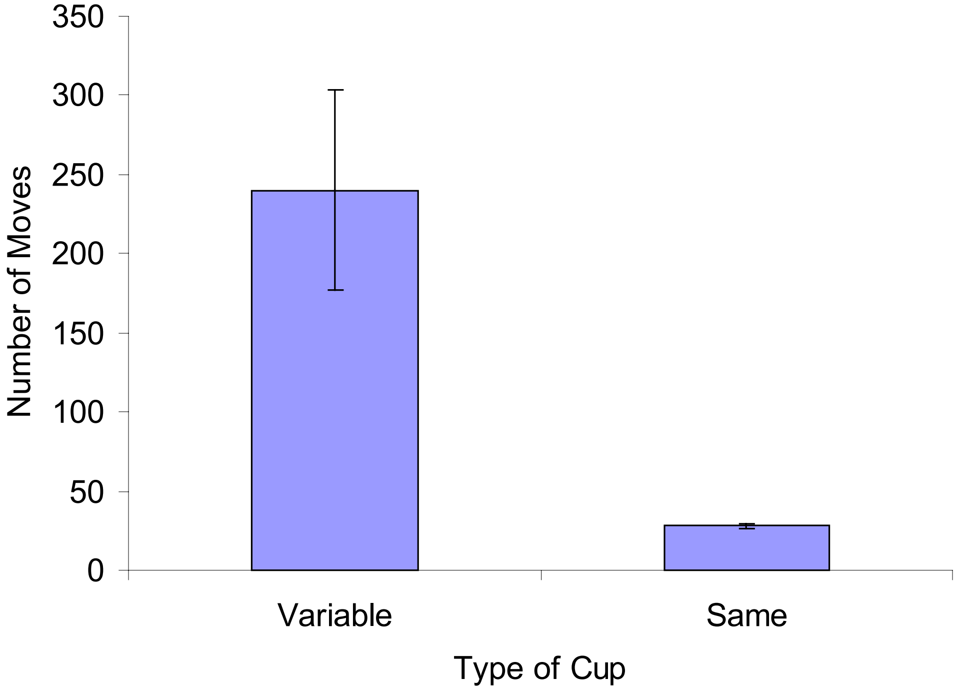


Figure 8. Mean number moves per testing phase when manipulating variable-sized and same-sized cups.

Table 3.

<u>The number of moves of each combinatorial technique exhibited by each monkey in Experiment 2: Task Demands.</u>

		Strategy				
Monkey	Type of Cup	Pair	Pot	Subassembly	Total	χ^2(df=2)
Nick	Variable	28	25	42	95	5.2
	Same	0	0	24 *	24	55.85
Leo	Variable	27	19	29	75	2.24
	Same	6	4	21 *	31	16.71
Chris	Variable	73	202 *	69	344	99.84
	Same	2	13 *	10 *	25	7.76
Xenon	Variable	74	156 *	90	320	35.43
	Same	3	18 *	5	26	15.31
Jobe	Variable	123	248 *	83	454	97.91
	Same	6	18 *	2	26	16.00
Xavier	Variable	65 *	72 *	15	152	38.14
	Same	3	21 *	11	35	13.94

"*" Indicates the strategy used the most frequently, p<.05 based on a χ^2(1). If two techniques are marked, they are used at the same rate, but more than the remaining method.

subassembly, and Xavier primarily used both pairing and potting as compared to subassembly (See Table 3).

All six of the monkeys showed a preference for a specific combinatorial technique with the same-sized cups. Both Nick and Leo used more subassembly than potting or pairing. These two monkeys potted and paired at the same rate. Xenon did the opposite, using the pot method more often than either subassembly or pair, and used subassembly and pair at the same rate. Chris and Xavier used both 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 technique more often than subassembly or the pair method, each employed at the same rate (see Table 3).

Nick, Leo, Chris and Xavier both showed a significant change in strategy selection depending on the type of cup that was being manipulated. Nick and Leo increased their use of subassembly and decreased their potting when using the same-sized cups (χ^2 (1) =12.35 and 4.24 respectively, $p<.05$). Xavier increased the use of subassembly to a greater degree than he increased potting when using the same-sized cups (χ^2 (1) =4.02, $p<.05$). All four individuals who changed the pattern of strategy use based on the type of object to be combined used more subassembly moves and less pair moves when they were manipulating the same sized cups (Nick: χ^2 (1) =13.67; Leo: χ^2 (1) =5.14; Chris: χ^2 (1) =5.35 and Xavier: χ^2 (1) =21.66; $p<.05$). Only Xavier showed a change in pair and pot use based on the type of cup. He used more potting and less pairing with the same-sized cups as compared to the variable-sized cups (χ^2 (1) =10.43, $p<.05$; see Figure 9).

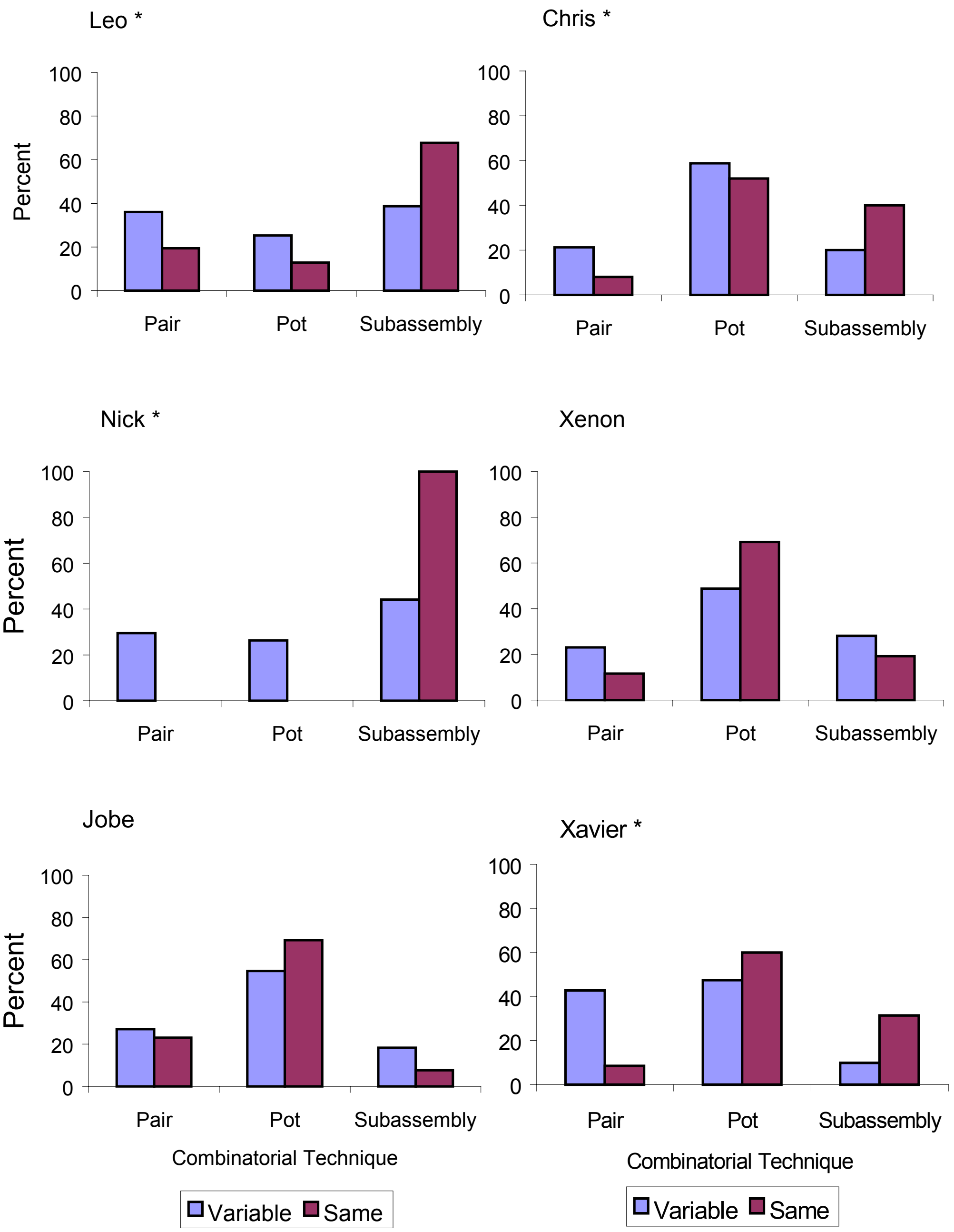


Figure 9. Percent each combinatorial strategy was used based on type of cup manipulated. An * indicates that the monkey's use of the different combinatorial strategies was dependent on the type of cup being manipulated (Leo: $\chi^2(2) = 7.45$, Nick: $\chi^2(2) = 24.14$, Chris: $\chi^2(2) = 6.51$, Xavier: $\chi^2(2) = 19.87$).

Based on the binomial probability of obtaining 31 out of 42 significant post hoc findings ($\underline{p}$= 1.13 x 10^{-31}) there are more significant results than would be expected by chance.

Discussion

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 strategy, unless it seriated the cups perfectly on the first attempt, it might have to shift strategies to fix a mistake in the structure. For both types of cups, some individuals used one technique more than the others. This indicates that the monkeys are not randomly using the combinatorial strategies. The least-used strategy (between pot and subassembly) decreased in frequency for all individuals and the more frequently used strategy increased for four out of the six monkeys when tested on the same-sized cups as compared to the variable-sized cups. The characteristics of the objects being combined and individual preferences influenced the techniques used to create nested structures. 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 while 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 strategies, rather it caused their most used technique to be expressed at a greater rate in four out of the six monkeys while manipulating the same-sized cups as compared to the variable-sized cups.

EXPERIMENT 3: SUBASSEMBLY TRAINING

Method

Subjects and Housing

Two monkeys (Chris and Xenon) participated in this experiment. These monkeys were housed together as a pair and previously demonstrated competency manipulating variable-sized cups to create stable structures using primarily the pot method (Johnson-Pynn, 1999). Housing, food and water were the same as in Experiment 1.

Apparatus

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

Procedure

Training. The two monkeys were explicitly trained to complete a variable-sized cup four-cup structure using subassembly. 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 method the largest of the four cups was presented. If the structure was completed using a subassembly strategy, the monkey was rewarded. If at any point after pairing the initial two cups the monkey used any technique 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 use subassembly preferentially were: 1) Six consecutive four-cup structures created with one pair move and two subassembly moves, and 2) One pair move and two subassembly moves on a probe trial where the cups were presented in the opposite order (largest to smallest).

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

Scoring and Analysis

After scoring each move for pair, pot and subassembly usage and the number and size of all completed structures, one pairing move was subtracted for each trial. The distribution of individual strategy preference in these trials was compared to the pattern previously exhibited (Johnson-Pynn, 1999) with the variable-sized cups prior to subassembly training using 2x3 Chi-square tests for independence. The number of moves per phase was compared for each individual using Chi-square goodness of fit tests.

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.

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 to 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 (χ^2 (1) = 109.34, and 39.24 respectively, $p < .05$; see Table 4). Chris decreased his total number of moves by 65% while Xavier reduced his total combinatorial attempts by 44%.

After subassembly training, Xenon used the three strategies at different frequencies, using subassembly at significantly greater rates than either pot or pair. Xenon used pair and pot at the same rate. Chris also showed a significant preference between the techniques favoring subassembly over potting. Pairing was used at a rate that was intermediate between subassembly and potting, although it was not significantly different from either of these other techniques (see Table 4).

The monkeys differed in the way they combined the objects depending on the training that they had received (Chris: χ^2 (2) = 47.68; Xenon: χ^2 (2) = 28.86, $p < .05$) based on a 3 x 2 Chi-square test of independence (see Figure 10). For both monkeys, after specific subassembly training, the relative use of subassembly increased while potting decreased (Chris: χ^2 (1) = 40.32; Xenon: χ^2 (1) = 24.75, $p < .05$).

Based on the binomial probability of obtaining 31 out of 42 significant post hoc findings ($p = 1.57 \times 10^{-8}$) there are more significant results than would be expected by chance.

Discussion

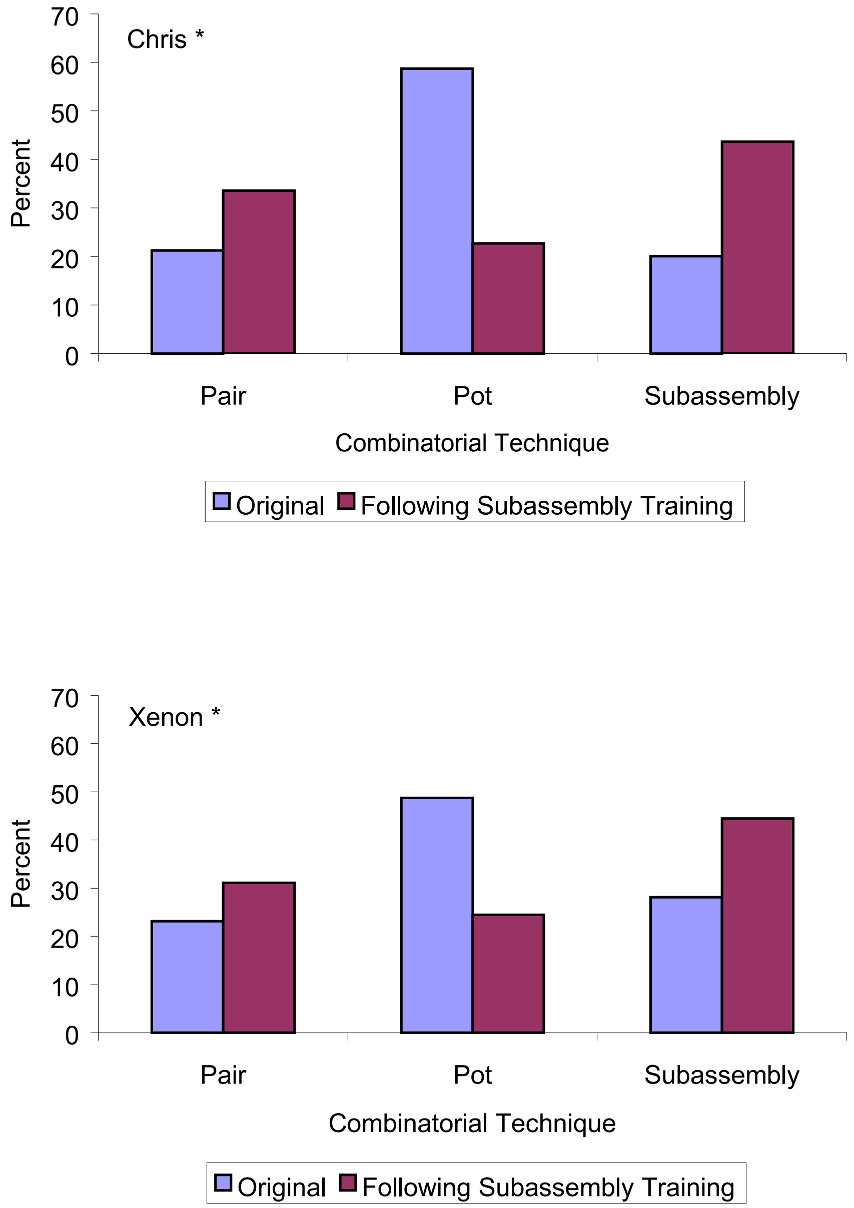
The nature of prior experience with combining cups does affect the manner in which cups are combined into structures. The short training in subassembly methods was sufficient to change the response trajectory such that both individuals reduced the amount

Table 4.

The number of moves of each combinatorial technique exhibited by Chris and Xenon in Experiment 3: Subassembly training, compared to their original performance (reported in Johnson-Pynn et al, 1999).

		Strategy				
Monkey	Training	Pair	Pot	Subassembly	Total	χ^2 (df=2)
Chris	Original	73	202 *	69	344	99.84
	Subassembly	48 *	27	52 *	127	7.88
Xenon	Original	74	156 *	90	320	35.43
	Subassembly	64	44	80 *	188	11.20

"*" Indicates the strategy used most frequently, p<.05 based on a $\chi^2(1)$. If two techniques are marked, they are used at the same rate, but more than the remaining method.



<u>Figure 10.</u> Percent each combinatorial strategy was used based on type of training history. An * indicates that the monkey's use of the different combinatorial strategies was dependent on the type of cup being manipulated (Chris: $\chi^2(2) = 47.68$, Xenon: $\chi^2(2) = 28.86$).

that they used the pot method and increased the relative frequency they used the subassembly method. This is similar to 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 using a sequential strategy. The children who were unable to initially complete this task were able to utilize the sequential strategy when given verbal and non-verbal feedback and were able to adopt this hierarchical strategy within 10 trials. Like the monkeys, the children were able to engage in complex hierarchical behavior, after brief instruction, even in the absence of hierarchical language abilities.

While each 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, but this is exactly what occurred. It might be that in learning to use subassembly, the monkeys also learned to better plan and order the cups. Both of these factors could lead to an increase in subassembly with development.

GENERAL DISCUSSION

These findings viewed together change the way combinatorial manipulation of cups can be interpreted. In all three experiments aspects of the environment and the experience of the individual altered the monkeys' combinatorial behavior. As monkeys do not demonstrate language abilities, the existence of individuals who primarily use the subassembly method to create stable structures weakens prior explanations (Greenfield et al., 1972) for how and why this strategy comes into use. If there were a central conceptual limitation on the methods an individual could utilize, it would not be possible to switch to a new dominant strategy in less than two days of training as both Chris and Xenon did. Experience could also cause the developmental shift towards the pot and then subassembly strategy seen in children, rather than a qualitative change in how children organize their behavior. However, based on the fact that 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 using fewer moves, there is a possibility that there is a qualitative change in combinatorial behavior associated with subassembly training. The only way for an individual to reduce the number of moves required to complete the task would be to know about the correct order that the cups to fit together. It is possible that the monkeys learned about this order during the subassembly training. But, considering the relatively few trials that 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.

Dynamic systems theory not only accounts for the findings in this particular set of experiments, but the transitions between combinatorial strategies in children as well. As children mature, they encounter more situations where 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.

Although the combinatorial activity of children has not been compared when different types of objects are being combined, it is likely that they would also show a change in strategy based on the demands of the objects they are manipulating. This leads to the prediction that they would progress through the different techniques 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 there is a clear influence making one technique a better choice than the other methods of combination, 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 towards the typical behavior observed in older human children and adults. This type of transition to a higher than expected developmental state is easily explained by a dynamic system where a change in any one variable can alter behavioral outcomes. In the future, in both humans and non-human 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.

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Appendix

A Review of the Literature

The organization of manual activity has been thought to be an indicator of cognitive abilities in humans (Piaget, 1954). Piaget's stages of sensory-motor development show a progression in motor development that is linked to the cognitive abilities required to perform such actions. In species where language cannot be used to understand cognitive abilities, manual activity and object manipulation can be a window. The different ways in which objects are manipulated can make a strong statement about the comparative complexity of a species' cognitive abilities. While primary object manipulation is solely body contact with an item, secondary object manipulation involves the use of one object with another, such as banging two objects together. This is where the view of object manipulation as a precursor to higher cognitive abilities such as tool use becomes apparent. The species that have been shown to use more secondary object manipulations are the same species that have been shown to be able to use tools, and more importantly, to develop their own tools without training (Torigoe, 1985).

Object manipulation is something that can and does occur in many primate and non-primate species and occurs in both laboratory (Natale, 1989; Renner et al, 1992 and Negro et al, 1996) and field settings. The research in this area has been experimental (Westergaard, 1994) and observational, the latter occurring in both the field (Bard, 1995 and Starin, 1990) and in captivity (Starin, 1990). Capuchins in particular are prolific and proficient object manipulators showing a wide variety of different types of manipulative activities including behaviors that would be classified as Piaget's secondary manipulations (Torigoe, 1985; Natale, 1989; and Fragaszy & Adams-Curtis, 1991). In this respect capuchins are more similar to the great apes than other monkeys. Capuchins show considerable variety in their actions with the same object, the number of objects used in the same act, and the frequency and proportion of relational behaviors. This is supportive of the notion that the large generation of new activities could be a precursor to the use of objects in a functional manner and that this is in the realm of capuchin ability.

Combinatorial manipulation, placement of two or more objects in relation to each other, was investigated by Greenfield et al. (1972) in children between the ages of 11 and 36 months with the goal of demonstrating a mechanical grammar that parallels linguistic grammar by investigating how children seriate a set of nested cups. Three primary strategies were identified: pair, pot and subassembly. It was suggested that the pair strategy was the grammatical equivalent to a simple two-word sentence. Two cups are combined. The pot strategy is more like a compound sentence with the two parts combined with the conjunction "and." For instance "cup A is placed in cup B <u>and</u> cup C is placed in B." In this scenario, the two halves of the sentence are equivalent and this sequence could easily be reversed. Greenfield et al. described a third strategy, subassembly, as the most advanced and complex. This mechanical action is depicted as the mechanical equivalent to a relational sentence, "cup A is placed in cup B <u>which</u> are both placed in cup C." This is different from the pot strategy because the order of events changes the meaning of the sentence. It is proposed that the use of this hierarchical strategy requires planning. Another difference between this strategy and all others is that there is a transfer of roles for each cup. The newly formed structure no longer is the receiving object but becomes an active object that is treated by the child as a single unit, rather than a structure with multiple cups.

A similar logic has been used to describe the development of representational play behavior and its relationship to language (McCune, 1995). Children showed five distinct levels of play: pre-symbolic play, self-pretend play, other-pretend play, combinatorial play and hierarchical pretend. These play types emerged sequentially in children. Combinatorial play, like the potting strategy, involved linear use of objects in play. They were considered linear because the play sequence was characterized by the same action with multiple objects. Hierarchical pretend, like subassembly, demonstrates flexibility in the roles of the objects.

Greenfield et al. (1972) support the idea of linguistic and mechanical parallels based on the fact that as children mature, they progress through pair, pot and subassembly in the same order as they demonstrate linguistic grammar. Although children did exhibit the mechanical grammar at slightly different ages than the corresponding linguistic stages, Greenfield et al. proposed that the same central mechanism was responsible for the development of both grammatical systems. Greenfield (1991) proposes that this mechanism is based in Broca's area and that in humans, up until age two this area is undifferentiated, but distinct areas then develop that are responsible for hierarchical organization of both language and object manipulation. Since non-human primates have a brain area that is very similar to Broca's area, this could be a pre-adaptation for language that developed prior to the evolutionary split between humans and apes. This brain region may be responsible for many other complex cognitive behaviors such as visual hierarchical processing and music performance (Givon, 1998). However, Swann (1998) contends that just because motor and speech control are located near each other in the brain that does not necessarily provide evidence that these two areas are linked, and if anything, Greenfield's link between language and motor skills should be viewed as an analogy and not a true homology. Unfortunately, as of now the technology does not exist for the functional mapping of structure construction and language in such young children (Greenfield, 1998).

If language and more general hierarchical planning abilities were indeed linked, then it would follow that children with language impairments should have similar problems with construction tasks, but this is not the case. When tested with multiple construction tasks of varying difficulty children with language difficulties were able to perform at the same level as those that did not have language impairments. Similarly, those individuals who were not initially able to solve the most complex construction task were quickly able to learn to solve it using a sequential technique. If there were a central deficit to be overcome, it is unlikely that a few demonstrations would be an adequate remedy.

Since the nesting cups used to assess these strategies must be stacked in a particular order, there is the possibility that errors will be made. The development of this skill should include not only improvements in avoiding errors, but also a better ability to fix errors once they have occurred. DeLoache et al. (1985) found that older children (42 months) could seriate a set of cups even if they initially made errors, while the younger children were more likely to seriate when there were no errors. Although all children were equally able to detect errors, the younger children were less adept as remedying mistakes. This difference may be due to the method used to correct the error. Older children were more likely to use correction strategies that reordered the cups rather than forcing the cups or decomposing the stack and starting over. Reordering the cups was correlated with the use of subassembly, which is expected since both actions involve a changing role for the cup that is being manipulated.

Non-human primates use the same strategies for combinatorial manipulation as humans (Matsuzawa, 1991; Westergaard, 1993; Westergaard & Suomi, 1994; and Johnson-Pynn et al., 1999) Infant baboons increase the frequency of combinatorial bouts during object manipulation from 1 to 6 months (Westergaard, 1993). Westergaard and Suomi (1994) found that when capuchins were provided with a set of nesting cups, they did manipulate and combine them spontaneously. Seven of the ten monkeys tested displayed pairing behavior, five used potting to combine the cups and three utilized subassembly. Even though each of the strategies was employed by at least a few individuals, pairing accounted for 91% of all combinatorial behaviors.

Johnson-Pynn et al. (1999) compared the strategies used by chimpanzees, bonobos and capuchins. The apes were initially much more active in creating more and larger nested sets, but once the capuchins received training to orient them towards the task there was no difference in their abilities. There were members of each genus that were proficient at nesting a full set of six cups. Some of the apes in this study had been conversationally reared and though they might be expected to exhibit a more advanced mechanical grammar based on their training with linguistic grammar, this was not the case.

Since Greenfield's approach may not sufficiently describe the developmental progression that occurs, a new perspective is needed. The dynamic systems approach is able to fulfill the goals of a good developmental theory (Thelen and Smith, 1994). It explains the origins of new behaviors. It describes how common behavior patterns could emerge from a diverse set of situations. It allows for data to be interpreted at multiple levels of explanation. It allows for a biologically possible, non-reductionist description of developmental phenomena. It elucidates how a specific local occurrence could result in a more generalized process. And, it provides a theoretical framework for interpretation and generation of new data (Thelen & Smith, 1994).

As a theory a dynamic systems approach is appealing because of its content non-specific nature. It can be used to describe situations as distinct as the origin of the universe to the way a mother laughs with her child (Nwokah et al., 1999). Dynamic systems can be used to describe normal childhood development (Thelen & Spencer, 1998; Bosman & Van Orden, 1997; and Clark & Phillips, 1993), the structure of adult motor skills (Sternad, 1999; Wulf et al., 1999 and Whitall & Getchell, 1996) and the differences between healthy and otherwise impaired individuals (Ulrich et al., 1998; Maida & McCune, 1996 and van Emmerick & Wagenaar, 1996). One common criticism of dynamic systems theory is that though it is a powerful tool for describing data in a post hoc manner, it is not always useful for creating models and making predictions. These primarily empirical research articles demonstrate a number of ways that dynamic systems theory has been used to form hypotheses about specific behavior patterns. In each case the predictions based a dynamic model have been supported, providing a clearer understanding of both dynamic systems theory and the development of the specific behavior under investigation.

These distinct fields are all viewed with the common perspective that the individual behaves in a manner that is the dynamic result of natural predispositions that interact with the natural mechanical patterns of the organism and it's environment. Since there are biological constraints on behavior, diverse biological and environmental influences will result in only a limited number of potential behavioral outcomes. Similarly, as an individual repeats performance of the same behavior, this experience will result in more and more circumstances that will result in the same behavioral outcome. With experience comes the stable behavior pattern that it expected of an expert in any particular skill. As a child learns to walk, the gait pattern starts out as highly variable, but then matures into the typical adult stride that shows highly consistent patterns of thigh/shank movement and coordination typified by cyclic clockwise trajectories (Clark & Philips, 1993). The analogy of a landscape with multiple valleys is typically used to describe how these complex behaviors arise from natural phenomena. The valley represents the occurrence of a behavior. The landscape is a two-dimensional grid where all possible physiological and environmental combinations of influence are represented. Since there are multiple valleys in the landscape, there are multiple related behaviors that could be elicited based on the particulars of the specific context. For instance, in certain circumstances an individual would crawl, walk, stroll, limp or run. The important part of the analogy is that the valleys are not all the same size. In an adult human, the valley representing the behavior “walk” would encompass a greater area on the landscape than the valley corresponding to the behavior “limp”. That being said, there are certainly physical circumstances, such as an injury or environmental circumstances such as acting in a theater production, that would create a dynamic where the less common behavior would be the one that is expressed.

Another implication of this analogy is that as individuals become more experienced at a particular behavior, the area that its corresponding valley represents in the landscape grows larger. This will result in the stable behavior indicative of skill and mastery. This analogy also helps to account for the development of new behaviors. As a valley encompasses a greater area, new behaviors may develop in the basin of the larger valley. For instance the expert runner may further specify this behavior when sprinting, distance running and cooling down after a race. Again the dynamic interaction of physiological and contextual cues would dictate which behavior was utilized.

While this approach has been used primarily to describe motor development, cognitive skills such as spelling and social communication have also been described using this approach (Bosman & Van Orden, 1997 and Nwokah et al., 1999 respectively). In English there are almost twice as many ways to misspell a word as compared to mispronounce a written word even when remaining in the rules of the English language. Based on these rules, and the fact that there is immediate feedback for errors in pronunciation but not for spelling errors, connections between pronunciation and the written word is stronger than the association between words and their spellings. As in any dynamic system when events are repeated in diverse contexts with stable outcomes (correct pronunciation), the skill develops, when the solution is not as salient, the behavior (spelling errors) will be more variable (Bosman & Van Orden, 1997).

In a dynamic view all influences can impact the expression of a behavior, but some are better predictors than others are. Another aspect of dynamic systems theory is that meaningful analysis must somehow isolate a few variables that are influential in the outcome of any given behavior. The essentially limitless degrees of freedom must be reduced to one or two control variables. Without this data reduction, the complex non-linear interactions between so many variables would be difficult to impossible to interpret or use in any predictive manner.