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Ordering and Executive Functioning as a Window on the Evolution and Development of Cognitive Systems

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We summarize some key features of our comparative and developmental programme at Edinburgh with particular reference to serial ordering and executive control as a window on the growth of cognitive competences in both evolution and development. Based on research on relational rather than associative learning mechanisms, we first argue that nonhuman primates share some core conceptual representations supporting semantic and rational development in humans. Reviewing recent findings from comparative work on seriation and classification, we also show that non-human primates can use ordering mechanisms similar to those that emerge during human development. From theses analyses, we argue that key features of thought and language have strong evolutionary precursors.

Contemporary human culture represents a high level of adaptation in which cognition plays a crucial role. We are surrounded by signs and symbols that convey knowledge by repute, use symbols to count and measure, and conjure with plans for possible action letting our ideas die in our stead in the case of hazardous outcomes (Popper, 1972). With high adaptive utility, our symbolic representations enable us to count and take numbers (and not necessarily sheep) to the market, guide actions via diagrams when constructing complex objects, and to use maps which eschew the need to learn each potential route *de novo*, and enable us to navigate economically over large spaces (McGonigle, 2001). And all of this comes courtesy of the combined effort of a "society of minds" to construct, alter and evolve knowledge conveyed in externalized symbolic representations in a runaway process which goes far beyond individual achievements (Donald, 1991; Wills, 1993). These very public manifestations of cognition in action leave us, nevertheless, with largely unresolved questions concerning cognition's evolutionary history. For as Wundt (1898) pointed out, the symbolic medium in which such achievements are conventionally expressed in human culture - in a world of language, books and other externalised forms of cognition - makes it impossible for the investigator to separate the role of culture from 'natural' knowledge growth in humans. As Bruner (1990) has also pointed out, moreover, the pedagogic influence on the child at school is culturally determined from the outset. In a home setting also, the "narrative" from mothers directed at children can be "relentless" (Bruner, 1990, p. 83). So what children actually discover for themselves when immersed in such a rich cultural milieu and directed by the speech of caretakers to attend to

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critical features of their environment is a complex question (Vygotsky, 1962), and some would say, still a largely neglected one (Lock, 1993). As a consequence, issues central to human cognition such as the relationship between thought and language (let alone their evolutionary origins), have been largely speculative and generally refractory to experimental analysis (Love, 2004).

For many involved in such debates, however, there is a growing consensus that primary conceptual representations critical for language, must exist outside language itself (Harnad, 1990; Haugeland, 1985; Jackendoff, 1993). An implausible alternative is to believe that what is essentially an arbitrary sound system has magically scaffolded an association learning system (McPhail, 1998). A third scenario is that a double mutation has occurred where combinatorial syntactic aspects of language as a communication system have coincided with a quantum leap from arbitrary association learning to a much more powerful system of coded representations of concepts that can couple with words to support meaning (Fodor, 1998).

Given the need to provide a scientific resolution of these issues, interest has never been greater in comparative and evolutionary approaches designed to uncover evidence for antecedents of conceptual thought (Gibson & Ingold, 1993; Goldin-Meadow & Zheng, 1998; McGonigle & Chalmers, 1998, 2001, 2002; Terrace & Metcalfe, 2005; Wills, 1993) and indeed language itself (Hauser, Chomsky, & Fitch, 2002). Debates within the domain of linguistics, for example (Bybee, 1998), have raised new and persistent demands for evolutionary answers especially since recent ground-breaking papers speculating on human linguistic origins from gesture (Corballis, 2002), imitation and mirror cells (Arbib, 2005; Rizzolatti & Arbib, 1998), and the property of recursion (Hauser et al., 2002).

Traditional comparative psychology is ill-equipped, however, to take on board the challenge. Based conventionally on paradigms that stress universal associative learning principles revealing only quantitative differences between species irrespective of vast differences in brain size and complexity, McPhail (1998) concludes “all vertebrate animals form associations and it has been very difficult to show there are other, perhaps more sophisticated, differences between their intellects” (p. 127). The result has been an overdependence on a relatively weak inductive mechanism, rejected by cognitive and linguistic researchers alike as one that cannot scale up and deliver teachable cognitive or linguistic skills (Chomsky, 1980; Gazzaniga, Ivry, & Mangun, 1998; McGonigle & Chalmers, 1996; Piaget, 1971). This failure to secure comparative evidence on qualitative as well as quantitative differences in intelligence leaves a conceptual vacuum in which language looms as a “magic bullet” invested with new capabilities of its own and putatively causal to the cognitive abilities unique to humans. With few options now left to him, following his characterization of intelligence just cited, McPhail (1998) concluded “we humans could…be regarded as (association forming) animals with language” (p. 127).

In this paper we endorse the view that there must be private codes in place which ground linguistic symbols to create sense (Haugeland, 1985), as meaning cannot come from an arbitrary sound system itself. Such codes, however, need to be tied to an objective reality capable of being shared by others for it ever to support a language. We shall argue that core relational mechanisms that antedate linguistic ones have such a capability. In the human, from the culturally evolved symbol systems of mathematics and logic to the everyday use of comparatives in natural languages such as in the terms *bigger than* and *smaller than*, and in the declaratives "John is bigger than Mary" we see expressions dependent on relational understanding. Their objective grounding lies in the (nonarbitrary) relationships between physical objects. In the first part of this paper, we demonstrate within an empirical comparative program how a system of such relationships emerges in a trajectory impressively similar in monkeys and children. In simians, however, we conclude that these remain as private codes, until their *externalization* into a public domain is made possible though the vastly improved manipulation skills of humans (Tallis, 2003).

The status of the private codes available to the agent is intrinsically related, moreover, to the syntactic and control issues that influence the way human language can combine and recombine a finite number of such codes (as words) to create an infinity of meanings (Pinker, 2000). In sentence production, for example, hierarchical organization enables the speaker to vary the ordering of a relatively small number of units (words) to achieve a wide variety of meanings—an example of a recursive property that is seen as embedded within a specific language competence termed "faculty of language in the narrow sense" by Hauser et al. (2002, p. 1571). A central and unresolved question, however, is whether such organization is an exclusively linguistic property of the human mind or whether it derives instead from a separate cognitive apparatus that owes its origins to the evolution of sophisticated controllers for actions which need to be sequenced to make adaptive sense (McGonigle & Chalmers, 2002). At the heart of this issue is the extent to which nonhumans have evolved hierarchically organized serial control enabling a flexibility in the control of action well beyond the brittle chaining of instinctive behaviors (Schneirla, 1959; Tinbergen, 1951). Here we provide evidence (McGonigle, Chalmers, & Dickinson, 2003) that monkeys indeed have powerful, hierarchical control devices operating to seriate economically in tasks which require the principled ordering of long sequences. Contrary to recent claims by Conway and Christiansen (2001) and Christiansen and Kirby (2003) that such organization is uniquely human, we argue instead that the seriation competences we analyze in simians may form part of advanced generic control mechanisms for ordering finessed in human evolution to produce a syntax for language and action alike.

Core Conceptual Representations from Relational Connectives

Simple declaratives are indisputably rooted in one object's relation with another and are open to verifiability. At the level of choice, however, what is the evidence that nonlinguistic subjects can compute such differences relationally? Here comparative evidence from nonhumans is crucial, although indeed for a long time, evidence for relational codification by animals was resisted as an artifact of bad procedure, explicable in absolute value and association learning terms (Reese, 1968). However, as reviewed by Tomasello and Call (1997), contemporary evidence for relational rather than association learning by nonhumans is strong if not systematic. At Edinburgh, following a series of some 25 experiments lasting nearly 2 years (McGonigle & Jones, 1978) where squirrel monkeys were required to code size and brightness stimuli relationally as compared with a comparison group required to code on an absolute basis, we concluded that the relational code was a design primitive, not reducible to a set of discrete associative stimulus-response connections based on absolute size.

A significant feature in these studies was the transfer opportunities offered to the monkey, as compared with conventional LS studies where the pairing of stimuli is ad hoc and arbitrary, and the subject can perforce only manage 50% correct on the first trial of any new discrimination (Harlow, 1949). In the course of our studies by contrast, the operation of a relational code such as bigger/biggest enabled monkeys to predict which (novel) object to select, despite variations in the training context (such as changes in the absolute values of the stimuli). As Trial 1 performance in these conditions was well above chance, we were able to infer that a genuine rule controlled choice prospectively, as opposed to the operation a rapid error recovery process based for example on a win-stay, lose-shift strategy. Findings such as these have been replicated by others using broadly similar procedures (see Tomasello & Call, 1997).

Now revealed, this competence led us to speculate on the combinative power of binary relational encoding in simians. As a consequence, one extension was into the area of linear transitive inference—a classic test of reasoning demanding the ability to combine relations such as A is bigger than B and B is bigger than C into a serial structure affording transitivity of choice between A and C. This normally demands linguistically competent participants where predicate arguments such as “John is bigger than Mary” can convey a John/Mary relation without enabling the subject to perceive the crucial test size differences directly. In our first venture (McGonigle & Chalmers, 1977), we adapted a test of transitivity used by Bryant and Trabasso (1971) for very young children to make it suitable for use with animals. Reviewed extensively elsewhere (McGonigle & Chalmers, 2002), the essential features were to train squirrel monkeys on 4 connected pairs of circular tins varying in color (A vs. B; B vs. C; C vs. D; D vs. E) first in an order congruent with a series, as above, then in a randomized order until monkeys achieved a very high level of success on all pairs. Only then did tests of transitivity take place involving all 6 novel pairs remaining from the 5-term series. Four of these were the training pairs. To ensure the possibility that some form of relational code could be utilized by monkey, rewarded tins were either heavy or light (counterbalanced like color assignments over all subjects). Weight was used as it is not a mediate property of objects that can be viewed directly—so no direct perceptual solution was possible here.

The outcome was the first demonstration of choice transitivity under the most stringent conditions developmental and experimental psychologists have been able to devise (McGonigle & Chalmers, 1977). So far, with the possible exception of a spatial case (Roberts & Phelps, 1994), the study is the only one that has given a nonhuman subject the opportunity to solve the task relationally, has shown high levels of performance when tested on an unblocked, one-trial basis, has provided special transfer tests to assess the basis for choice in the binary conditions, and has recorded extensive decision-time assays (McGonigle & Chalmers, 1986, 1992) to produce the first symbolic distance effect (SDE) in nonhumans (replicated using a serial-learning paradigm by D’Amato & Colombo, 1988, and Brannon & Terrace, 1998). In addition, we followed these experiments with cognate transitivity experiments with children as old as 6 years (Chalmers & McGonigle, 1984) to evaluate the extent to which the profiles for simians differed qualitatively or quantitatively from those of children (Bryant & Trabasso, 1971). We compared the behavior-based method as used with monkeys with one also providing linguistic instructions. Significantly, language added nothing to the child's performance. We found no evidence whatsoever that children and monkeys differed on any of the key points of comparison at both the macro and the micro level (see McGonigle & Chalmers, 2002, for an extensive analysis).

The simian experiments were long-term, featured many conditions, and provided us with rich signatures based on both choice and decision time. Consequently, Harris and McGonigle (1994) were also able to provide a formal account based on production systems in which individual subjects were modeled based on a rule stack. These modeling attempts indicated that great care has to be taken to distinguish a variety of mechanisms that can give rise to transitivity. As we pointed out (McGonigle & Chalmers, 1977, 1992), both subjective and objective factors may be implicated. For example, as we cited in McGonigle and Chalmers (1977), unidimensional stochastic models of choice (Luce, 1959) can provide a candidate mechanism based on a subjective dimension that Berlyne (1965) and Bradbury and Nelson (1974) suggested is prelogical in young children and is derived from scales such as niceness. Thus, children can be tested on their ranking of color for attractiveness such as Yellow over Blue, Blue over Red and subsequently tested on transitive preferences for Yellow versus Red. This basic subjective ranking mechanism is an adaptive one, and shows a developmental trend in that children become more consistently transitive under these conditions (Bradbury & Nelson, 1974). It is almost certainly implicated in simple transitivity of the sort reported (e.g., Couvillon & Bitterman, 1992; Wynne, 1998) in a variety of species, and indeed in foraging and other so-called rational forms of decision making (Schuck-Paim & Kalcenik, 2002). It must not be confused, however, with ranking mechanisms based on a material scale of (for example) size relations demanding a switch from subjective to objective judgments necessary for logical inferences (Inhelder & Piaget, 1964) and the growth of objective world knowledge. That "John is bigger than Mary" and "Mary is bigger than Joe" are perceptual, objective facts if the differences between the objects of reference can be viewed directly by the subject. The predicate argument "bigger than (John, Mary)" is not a matter of subjective preference either, nor is the deduction "John is bigger than Joe", following as it does of necessity from the (relational) rules of inference (Halford, 1993; Piaget, 1928).

Transitivity paradigms, therefore, when based exclusively on behavioral techniques that rely on building up through training a subjective scale of what "wins" are inevitably doomed to having these two forms of choice control conflated. This leaves open the status of transitive choice behavior now reported in a variety of species (see Roberts, 1998, for a review) since our first report with squirrel monkeys.

Relational Systematicity in Monkeys and Children

As binary tests of transitivity can be solved with sparse rule sets (Harris & McGonigle, 1994), we sought to develop tests that demanded more explicit rule implementation. This requires multiple rule operation within a connected system where, for example, different objects in a size series conveyed simultaneously would attract codes such as biggest, smallest, second-smallest, middle, and second-biggest if named (exhaustively) by a human subject. Clearly this type of response is not an option for simians. So we developed a special color-based conditional discrimination procedure primarily as a technique to test monkeys' competence to assign an ordinal value to each object in a set on the basis of highly specific, systematic and objective relational computations. With a 5-item set, therefore, we employed 5 different colors to serve as instructions. Thus, for example, when all items were black, a monkey learned to select the biggest object in the set, when all objects were white, the monkey selected the smallest one, and so forth until the animals complied with all 5 instructions. One key feature of the paradigm is the concurrency requirement where all rules pertinent to the set of objects need to be operated by the same subject at the end of training to satisfy the task requirement overall. A schema illustrating the procedure is provided in Figure 1.

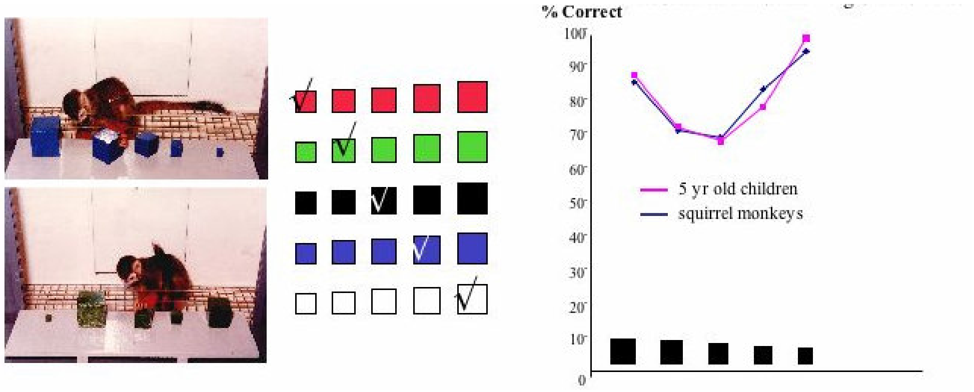

Figure 1. Squirrel monkeys (left) being trained on a series of 5 conditional rules of relation such that if all blocks are (e.g. red) then choose the smallest one, if all blocks are green, choose the second smallest, etc., until all 5 rules can be operated concurrently and in random order. Spatial position is random. Five year old children were given similar training and showed highly similar acquisition profiles as the graph illustrates.

Among the various possible scenarios we anticipated, a plausible one was the failure of monkeys to compute a relation and its inverse. Another suggested a rule limit, indexed by a lack of correspondence between the number of individually sized objects in the test set and those that could be identified uniquely. A third scenario was that monkeys acquired all 5 rules independently; crucially, however, was the issue of whether these could be operated concurrently. If so, it would give us a strong indication that the monkeys were operating the rules within an interconnected system—a behavioral manifestation of semantic systematicity (Fodor & Pylyshyn, 1988).

Five rule acquisition was achieved by randomly interleaving trial blocks of five, then two, and finally single trials on each rule until an 80% criterion was achieved across all five rules simultaneously. This was an important control here (McGonigle & Jones, 1978) against the monkey learning to switch following a nonreward rather than on the basis of a new rule. At these final stages of acquisition, the monkey's level of error stabilized somewhat below that of the five-year-old children used for comparison (McGonigle & Chalmers, 2002). However, the monkey's and children's patterns were highly similar during acquisition, as Figure 1 illustrates. Following original learning, monkeys showed high and significant levels of transfer to a new size set where only the ordinal values but not absolute size values were conserved. This transfer to new sizes is consistent with findings by McGonigle and Jones (1978) who found absolute size coding to be poor in squirrel monkeys, and very inferior to relational coding.

These experiments using color conditional-based relational codes have shown that a system of codes can be developed, derived from a single primitive rule of difference. In short, there is no evidence to support the case that the system has been installed by evolution as one whole enterprise. Instead, seeded from modest beginnings, the codes are minimalist at the outset (Chomsky, 1996) and there seems to be a principled syntax or assembly logic of these codes until the rule system caters for relational combinations within finite sets of the sort we feature here (for a fuller analysis of this, see McGonigle & Chalmers, 2002). This explicit 5-rule system is more complex, moreover, than was demanded (minimally) for transitivity in either monkey or young child. In the former case, each separate color conditional instruction changed the topic-reference relationship so that, for example, "if blue then second-smallest" is the topic and the rest are the reference. This topic-reference changes once a new color is featured. In this task, therefore, all stimuli are potential winners, in that each must be selected in competition with all others in the set depending on the rule involved by the color code. In contrast, binary choices in elementary transitivity tasks carry no such demands. Whereas B wins over A, C wins over B, with the final E stimulus winning invariantly over all of the other items (see McGonigle & Chalmers, 1986; Wynne, 1998, for model theoretic versions of this idea).

Systematicity apart, the task instructions when operated successfully as here imply an ability to map a set of arbitrary signs onto the relational structure of the test set—an impressive hooking of signs to representations. And the currency for the latter must be based on private codes or procedures, and not the objects *per se*. Here the shift from simple signs learned associatively such as "red" signs "food" (where red and food have internal correlates as physical stimuli) is replaced by a more complex codification such as "red" signs "second-biggest" (object), which signs food.

In summary, our characterization suggests that relational codes are computed in a systematic way by both monkey and child when confronted by tasks that demand unique identification of each item within a set. This demonstration of ordinal representation is not to be confused with coding ordinal position within a list (Chen, Swartz, & Terrace, 1997)—a temporal value that is not tied to a material dimension of comparison. Here, monkeys have mapped the instructions carried by the color codes to an objective difference relation, of which they must have some underlying representation. Our findings also show that these representations become elaborated and differentiated through the learning of their inter-connections. So some primitive semantic layer may be revealed here, constrained in scope more by the limits of the study than the potential competence of our simian subjects to operate semantically. In short, we argue that our learning-based assessments, which could be viewed from one perspective as exposing (i.e., bringing out) basic cognitive competences, are better viewed as bringing them on by use (McGonigle, 2004). And it is only in a laboratory context that these nurturing conditions can be provided in a principled way. Under natural conditions, by contrast, there is no guarantee that the ecology furnishes systematic challenges, let alone affords opportunities for supervised long-term learning of the sort we describe here, teaching that could match the "relentless" instruction accorded the child recipient of by adult caretakers (Bruner, 1990, p. 83).

So far, using principled, supervised learning akin to that used with children, we have exposed some basic layers of a representation system that could enable a mapping onto arbitrary sounds as in human language. This is hardly an implausible claim, given that we have already shown the ease with which the simian maps relational codes to an arbitrary set of color values so that they achieve some meaning at least for the individual subject. However, it is one thing to establish a vocabulary of such signs and quite another to show that simians have competences to combine and re-combine these vocabularies to support ordering of such signs or actions in tasks where planning and flexibility are at a premium. In this context, serial ordering of behavior provides an important window on the control mechanisms different species may adopt. *Insecta*, for example, are characterised by Schneirla (1959) as operating sequences of actions like finite-state machines. These are brittle and likely to abort when one of the successor links defaults (Tinbergen, 1951). Raising the stakes, however, to achieve more flexibility, costs more in wetware terms. Whereas the adaptive warrant for achieving this flexibility is clear and indeed quantifiable—ideally species should avoid the quick fix of first-order Markovian-type sequences and evolve something more pliant—the investment costs in engineering such competences for a genus like *Insecta*, as Schneirla (1959) pointed out, may be incommensurate with the returns.

On this scenario, one would expect that with large increases in brain size and complexity of the nervous system, new forms of serial control would be elaborated. As for actions that could be so analyzed, we confront a paradox. Only simpler organisms show characteristic serial patterns in the wild; more complex ones are opaque in this regard. Here specific training is clearly the answer, analogous to the program we described with squirrel monkeys. However, in this context both the paradigms used and the model or template of achievement against which simian performance may be gauged is crucial. Previous attempts for example to show grammatical competences in nonhumans through so-called "ape language" programs (Savage-Rumbaugh, 1986) have suffered from a lack of consensus as to the appropriate medium of training (McGonigle, 1987), as well as to the template for assessing language competence, depending on whether one uses the generative program of Chomsky (1965) or later alternatives (Chomsky, 1996), or follows the new functionalists (Bybee, 1998) or a sociopragmatic stance (Tomasello, 2001).

Size Seriation as a Window on Executive Control

Instead of a language-based template, we looked to human development for a behavior-based paradigm for assessing high-level serial control. An obvious candidate is Piaget’s test of size seriation in which children are asked to make a staircase, or copy a model of 10 rods of different sizes (Inhelder & Piaget, 1964). Young children (around 3 or 4 years) fail to seriate more than a few rods from a test pool. Later in development (5 or 6 years), they can approximate to the model using trial and error. Finally (around 7 years)—in what Piaget describe as “operational” seriation they can achieve spontaneous principled ordering of size, starting from one end of the series and selecting and placing every element without error. At this point, according to Inhelder and Piaget (1964), the skill of ordering becomes generative; that is, any number of elements can be ordered without trial and error, and items taken at random from the test pool can be inserted correctly into their appropriate place within the series.

Essentially a behavior-based skill, seriation offers a promise, therefore, of distinguishing between qualitatively different levels of control. The dramatic change in behavior at seven years is achieved, according to Inhelder and Piaget (1964) by insight into the logical structure of reversible relations (if A<B, then B>A). One consequence of this is that operational seriation is (they argue) independent of set size or the differences in size between and amongst the items (Inhelder & Piaget, 1964, p. 251):

> *We might have found a marked improvement in the seriation of length” (in preoperational children) “had we used fewer elements or if there had been greater differences between the elements. But either of these adjustments would have meant that we were measuring a perceptual adjustment to an intuitive whole instead of operational reasoning.*

In other words, children appear to move from a series of perceptually guided approximations of a series to a new level of control: systematic ordering based on the comprehension of ordinality in which every item’s place within the series can be determined "…bearing in mind that a given element say E is both longer than those already in the series (E > D, C) and shorter than the ones yet to follow (E < F, G)" (Inhelder & Piaget, 1964, p. 257).

For size seriation, therefore, we have a potential continuum of significant growth, where both the size of the test set and the style of production seem crucially important. Given that we had established a putative basis for explicit seriation in monkey using our color conditional procedures, albeit with only 5 test items and with each test halting after one object was selected, we set our sights at achieving the first convergence of human and simian size seriation (see McGonigle & Chalmers, 2002, for a review). To achieve this, we had to establish new paradigms using touchscreens that eschew the manipulatory restrictions on simians, requiring them merely to touch icons in predetermined size sequences. In a converging part of the program, we explored children’s seriation competences using the same common currency of test, training and analysis. In the next section, therefore, we first report some of our developmental results using these new methods.

Child Seriation and Executive Control

One question we needed to resolve was whether indeed operational seriation marked a fundamentally new facility for understanding size relations from the ones we had already explored with young children and monkeys in our size learning paradigms, and if so, what changes and what, if anything, is added to the system to enable the changes? On Piaget's classic account (Inhelder & Piaget, 1964), the new element is the grasp of reversible logic; in more contemporary terms, what has changed is the level of executive control. Executive function is "a still largely provisional" concept (Joseph, 1999, p. 310) but one that is commonly described as goal-directed behavior involving planning, working memory and flexibility (Pennington & Ozonoff, 1996; Russell, 1997). One way to conceptualize the move towards an apparently more planned behavior in the older child in terms of contemporary developmental theories is to assume that the planned goal is represented at a new level (Kendler, 1995), perhaps relationally more complex (Halford, 1993; Zelazo, 2003) or more explicit (Karmiloff-Smith, 1992)—in short, not explicable in terms of the type of control used by the younger child. In cross-sectional studies, however, it is impossible to tell whether the learning exhibited in younger children is already on accelerated trajectory and needs no other level to be invoked. Here again, seriation offered a potentially ideal paradigm. Explicit in its executive demands, it is highly measurable in terms of search and planning. Effects of set size and concomitant difficulties in searching and discriminating can be monitored on an item by item basis within and across sequencing episodes over time.

Size Seriation as an Executive Skill

Moving to touchscreens with such measurement criteria in mind, our learning requirements were for children to touch size items on the screen in a monotonic ascending or descending size order (Chalmers & McGonigle, 1997; McGonigle & Chalmers, 1996, 1998, 2001). Especially crucial, given the claims that young children can be influenced by perceived layout factors, all our touchscreen seriation tasks presented the size elements in random spatial layouts that changed from trial to trial. In no case was there any spatial consequence of a selection. Whereas children who seriate blocks can use the contingent proceeds of their own sorting as perceptual data, the array of icons on the touchscreen remained the same until each sequence was completed.

In our first experiment, 12 five-year-old and 12 seven-year-old children were confronted with random linear arrays of 5-item sets, each consisting of differently sized squares on the screen. In a second experiment with another 24 five- and seven-year old children, 7-item sets were presented. Two nonoverlapping and randomly interleaved size ranges were used in both cases to prevent absolute size learning. The children were trained by bleeps (correct) and buzzes (incorrect) from the computer to touch the items either in a descending or ascending sequence (see Figure 2 for an example of a 5-item set). A learning criterion was set of 8/10 sequences executed without any errors.

Figure 2 depicts the learning profile for these groups of children from which it can be seen that five-year-olds could be trained to seriate without errors but that set size significantly increases difficulty for this group, whereas seven-year-olds required little or no training on either set size. An important question on a growth model, therefore, is whether the competence displayed by the younger children shares the essential features of the skill shown by the older children, varying only in the level of executive control, or whether some entirely different skill has been entrained in the younger children from the one that appears relatively spontaneously later.

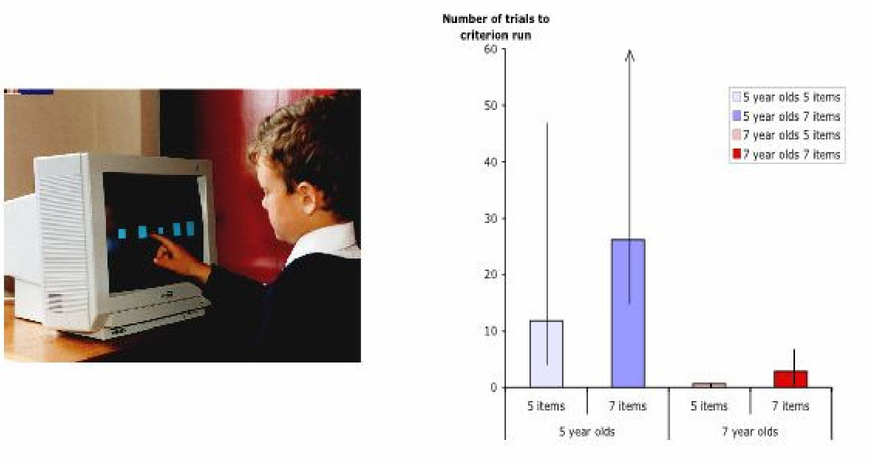

Figure 2. A five year old child (left) being trained on a touchscreen based size sequencing task. Auditory corrective feedback from the computer is used to train the child to touch the objects in a monotonic (ascending or descending) order to a learning criterion of 8/10 completely correct sequences. Spatial position is randomized across trials and two different size sets are used in random alternation. The bar graph shows errors during acquisition for five versus seven year olds and for 5 and 7 item sets.

Following on from his logical account, for Piaget (Inhelder & Piaget, 1964), a tiebreaker here was item insertion—the extent to which the child could identify the ordinal position of individual items within the set. Therefore, a second type of task given to all the participants in our seriation study was training of items' ordinal-size identification. One such task was a match-to-sample procedure in which the same two randomly interleaved size sets as used in the seriation task were presented on the screen. One was presented as a set of targets, the other as sample, each of which had to be matched to the corresponding ordinal size match from the targets. An example is shown in Figure 3 for 5-item sets, together with the summary results from five- and seven-year old-children.

As with the seriation task itself, the findings from this task showed that item ordinal identification is also a gradable skill that expresses itself as partial success in the younger, five-year-old group and that is subject to slow learning, but manifests as a more intact skill in the older children, who were all successful and who made few errors (see Figure 3). However, these data provide evidence to question the view that size seriation and ordinal size identification are integral abilities, with the appearance of one denoting the appearance of the other. This is evinced by the selective learning effort required by the two tasks. Whereas size seriation of five items was entrained in the younger children in around 12 trials, ordinal size identification by contrast was on a different scale of difficulty. On this latter condition, many subjects failed altogether even after training on 200 trials or more. (That this was not due to the matching requirement *per se* is indicated by identical difficulties found with another group of children using a color conditional procedure used also with monkeys that we describe above). So here we have a different ontology from Piaget's in which, if anything, the data suggest that size seriation is a causal precursor of ordinal size competence. This view was reinforced in a further developmental study in which we interleaved the two forms of task while gradually increasing the size of set as illustrated in Figure 4.

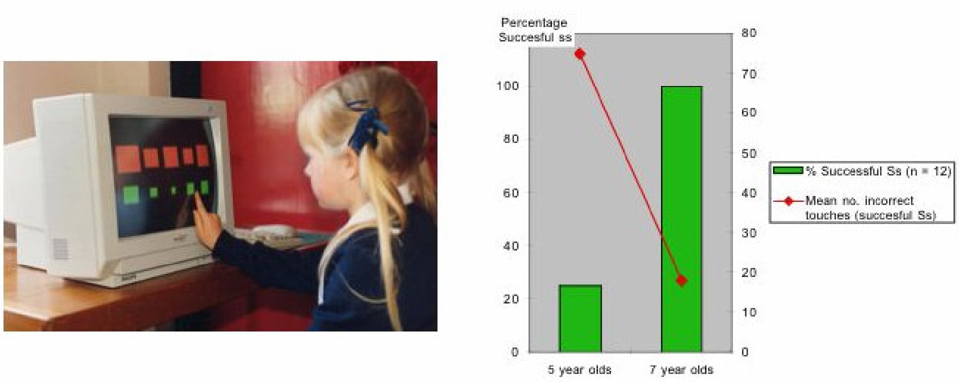

Figure 3. The Match-to-Sample task and results. A stimulus flashes in the upper row and the correct ordinal match must be touched in the lower row; corrective feedback is given via bleeps and buzzes from the computer, and up to 40 trials per size rule are given in all. The bar graph shows the age-related increase in the number of children reaching criterion within 200 trials, and the line graph shows the concomitant drop in the mean number of incorrect touches during acquisition.

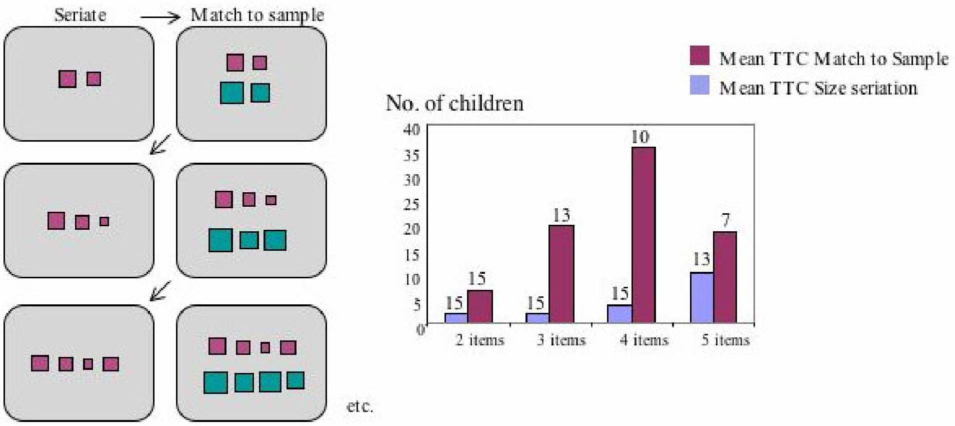

Figure 4. An interleaved paradigm in which 15 naïve subjects aged five years were given seriation training, followed by ordinal size rule identification training, where set size was incremented by one stimulus at a time. The numbers of children succeeding on each task is shown above the bars depicting their mean trials to criterion (TTC).

From this very direct intra-subject learning-based comparison across the two tasks, it was clear that in every subject, the skill of seriating was in advance of the skill of ordinal-size identification, and for the groups as whole, there was a marked discrepancy both in the number of children succeeding at each level of the task as well as in the learning effort of those who did, as Figure 4 illustrates. As far as the younger child is concerned, therefore, the implication was strong that the skill of identifying the ordinal position of every item in a set (as witnessed in Piaget's operational seriators) originate from serial behaviors dedicated to ordering objects in the world. In short, the rule-learning competences that we had previously unearthed in monkeys and children using the color conditional training with blocks had now been sourced to an executive mechanism based on principled unidirectional search.

New Levels of Human Serial Control?

From our training studies, the implication was also clear that the executive routines for controlling linear search were nevertheless still fragile in five-year-old children and not yet immediately generative to new set sizes. This was also clear from transfer studies in which five-year-olds were trained up to criterion on 5-item sets and then simply were given two more in new extended 7-item versions (McGonigle & Chalmers, 1996). As this spontaneous generativity is one of the behavioral criteria for assuming that 7-year-olds seriate by means of a new type of logical control, a question that remained concerned the extent to which our data supported this view. Certainly with this group, ordinal matching is as good as seriation *per se*, and both abilities appear to be at a ceiling performance at least for these set sizes. Whereas one explanation of this could be that true seriation is indeed based on new ordinal competences, timing analysis of the seriation and matching performance of 7-year-olds (with 7-item sets) shows that no such new layer of competence is necessary to account for their performance. Here, the time to reach any particular item (e.g., the third biggest) within the monotonic search was calculated through the cumulative inter-touch RTs recorded by the computer. These were used to generate predictions about the time it would take to for those same subjects to scan the targets in the matching task, and then find the appropriate match from the samples using principled serial search from one or other end of the series. The degree of fit between the obtained and the predicted was strong and significant, as Figure 5 illustrates.

The developmental program thus gave strong support for the view that executive functions deriving from serial behaviors can explain, on a continuity basis, the emergence of what appears on the surface to be caused by new layers of competence. The spontaneity with which the older child executes a seriation task does not therefore in itself indicate a new basis for solution, and we must conclude that these executive skills are already on accelerated trajectory by the age of five—perhaps to be further augmented by practice and expertise in tasks of a similar type, both schooled and unschooled that surround children of this age in numerous forms. An obvious feature of such an accelerated trajectory is the fact that the more successful the ordering, the greater the likelihood that children will discover its products—namely, well-formed assemblies in space—a cycle of causality that is hard to unravel in the human (McGonigle & Chalmers, 2001).

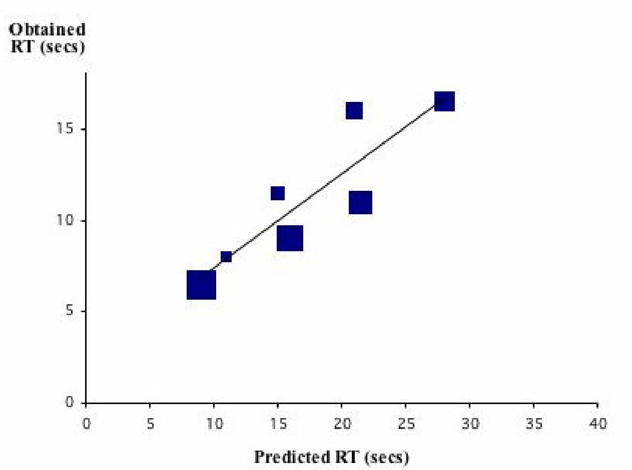

Figure 5. The fit between obtained RTs for size items (denoted from biggest to smallest by the relative size of the points on the graph) during correct Match-to-Sample performance by seven year old children on 7 item sets, and predicted RTs generated from their inter-touch times during 7 item linear size seriation.

Does this imply that there are no fundamentally logical achievements related to seriation as argued by Inhelder and Piaget (1964)? We would argue that there are indeed further skills related to seriation of a more logico-mathematical type, but that these occur well after seven years of age. Our analysis indicated that the cost of acquiring seriation expertise in early development is an adherence to a strongly unidirectional form of search. Given a nonmonotonic (and logically equivalent) sequence to order, (such as second biggest, middle-sized, smallest, second smallest, biggest), both 5- and 7-year-olds found this to be a dramatically harder task even for 5-items sets. Set expansion, furthermore, to nonmonotonic tasks with7-items disqualified all five-year-old children from even attempting the task, and most seven-year-olds failed to learn the sequences within 200 trials. Adults, however, could achieve success relatively easily, but usually with protocol evidence that they had converted the sizes to numbers. Our studies indicate, therefore, that whereas significant growth in early human development within the domain of relational understanding comes directly from executive control mechanisms and prolonged task exposure, new logico-mathematical skills emerging from these competences, such as counting and the number line, can extend the scope of such mechanisms into new realms.

An Evolutionary Continuum for Principled Serial Control?

Our analysis with children indicates that core competences for serial linear monotonic search can be revealed by explicit training. Whereas other factors may be implicated in the acceleration of such skills to the point that they appear in a spontaneous and untutored fashion, merely recording when such discoveries emerge denies the comparative exercise of analyzing change and the motive for change. In the case of linear size seriation, we have argued that the motive is one of economic search (Chalmers & McGonigle, 1997; McGonigle & Chalmers, 2001, 2002), itself prompted by having to deal with large amounts of information. Once an iterative rule is fully grasped in relationally based series, long sequences can be executed by generating a prospective search for the next item in the set. This is not without its own executive demands (prospective search can require considerable working memory where there are large random displays on the screen), and it is an empirical question as to normative limits on this type of control in typically (and atypically) developing children (McGonigle & Chalmers, 2003). Equally, it was an empirical question now open to investigation in monkeys, also. The squirrel monkey's success with the ordinal matching task suggested a solution highly analogous to that employed by children. Were monkeys also to show trainability in linear size seriation with evidence that they can show an intrinsically generative ordering capability, then it would be hard to resist that the conclusion that the monkey's relational skills are indeed homologous to those of humans. The path now lay open to us to use explicit training with monkeys to consider to what extent a cognitive competence for principled ordering exists in simians and whether it shows the same properties of economy and generativity as found in human development.

Seriation and Executive Control by Nonhumans

Most serial learning studies with nonhumans (see Terrace, 2005, for a recent review) feature arbitrary constituents, which strongly resemble rote-learning paradigms with humans. Eschewing the possibility of the subject establishing meaningful relationships between the items to be seriated limits the relevance of such paradigms to issues such as generativity. As in the case of the alphabet—learned purely by rote—there is no serial rule that would enable the learner to generate a principled ordering rule for new items. As for flexibility and recombination, moreover, the strictly supervised conditions of training with purely arbitrary elements also leaves little scope for recombinative competences unless the subject imposes phrasing or chunking on the strings (McGonigle, 1987). The use of category-based information based on similarity or equivalence, by contrast, makes this possible through the use of hierarchical organization (McGonigle & Chalmers, 2002), such as "all Xs before Ys"; "all Ys before Zs". In this event, a string of 9 putatively independent items (combinatorially explosive) reduces to 3 chunks, enabling recombination within a sequence where, for example, the first segment must be moved to the third position (McGonigle, 2004). In this way, planning and the recombination of serialized actions become possible. This has been implemented as an organizational principle in robots in our laboratory (Bryson & McGonigle 1998).

In short, generative mechanisms for action depend on the superior adaptive value of nonarbitrary relationally based sequencing, both linear and hierarchical. At issue, however, is the extent to which nonhumans share such competences. In a coordinated long-term program described in detail elsewhere (McGonigle, et al., 2003), with *Cebus apella* (two mature males and five mature females), we used the touchscreen seriation technique to answer these questions. In part of this program, described in the first section below, we evaluated the extent to which monkeys operate principled size seriation with long sequences, given that set size is a revealing factor in the development of seriation in children.

Linear Size Seriation by Cebus apella

Unlike the earlier child studies, the layout on the screen was based on a randomised array, as illustrated for 9-item sets in Figure 6. Monkeys were tested in pairs in a large test room. Each monkey had its own touchscreen that featured a 4 x 4 grid, providing for the simultaneous exposure of 16 items. A Plexiglas plate in front of the monitor had 16 hand holes drilled to allow the subject to reach each icon without swiping across the touch-sensitive screen, which would perturb the computer-based monitoring of legitimate sequencing. Testing began first with a period of pretraining to a single icon displayed randomly to appear in any one of the 16 possible locations, and with equal frequency. During this phase, each touch registered by the computer was signaled on the screen by a brief appearance of a white square around the outline of the icon selected and activated a peanut dispenser located on the left wall of the apparatus.

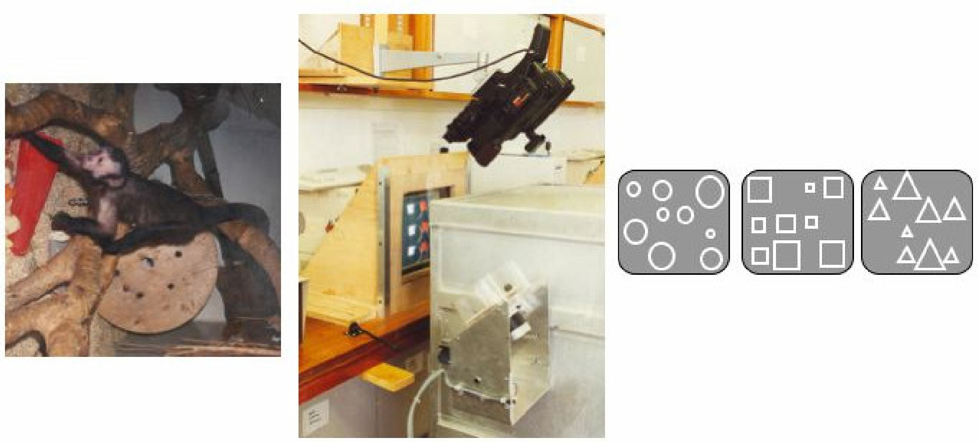

Figure 6. *Cebus apella* (left) in a colony room; the touchscreen setup (centre) showing the test cage, peanut dispenser and an example of a 3 by 3 layout on the screen covered by a Plexiglas plate with hand-holes; the actual stimulus displays (right) used in 9 item size seriation where monkeys were given 3 different categories of object to seriate in random alternation across trials.

The final phase of our investigation, (designed overall to test both linear and hierarchical organization in a series of phased episodes), culminated in a linear monotonic condition even more demanding than the one we gave to children. Here, the monkey was presented with a total of 9 sizes displayed in an entirely random configuration on a 4 by 4 grid on the screen (see Figure 6). Monkeys were required to touch the shapes in ascending order of size. A single error resulted in the screen going black and a one-second time-out before the display reappeared. Following prior exposure to different shape categories, monkeys were given three different shapes to seriate in random alternating order within a session. The exit criterion was 70% completely correct trials correct across all three categories within 50 consecutive trials.

The three monkeys who participated in this training (the others were withdrawn for breeding) were successful, converging on the high-level operational seriation performance of children over the age of seven years, as depicted in Figure 7. Moreover, their performance had all the hallmarks of well organized executive behavior, delivered in one smooth production, and very rapidly in the case of successful performance.

This is the first demonstration of size seriation in nonhumans requiring the type of behavior used by Inhelder and Piaget (1964) to describe operational seriation of size. For this cognitive skill to be demonstrated, a large number of items are necessary, and the production must be without components based on trial and error.[1] As the learning episodes in monkey and child are on a different time scale, and as children are exposed to linear ordering in many formal and informal contexts by the age of seven, it is hard to calibrate the monkey's performance against the child's in acquisition terms. However, all the indications are that the seriation by monkey is founded on the same (adaptive) control mechanism for ordering as found in human development.

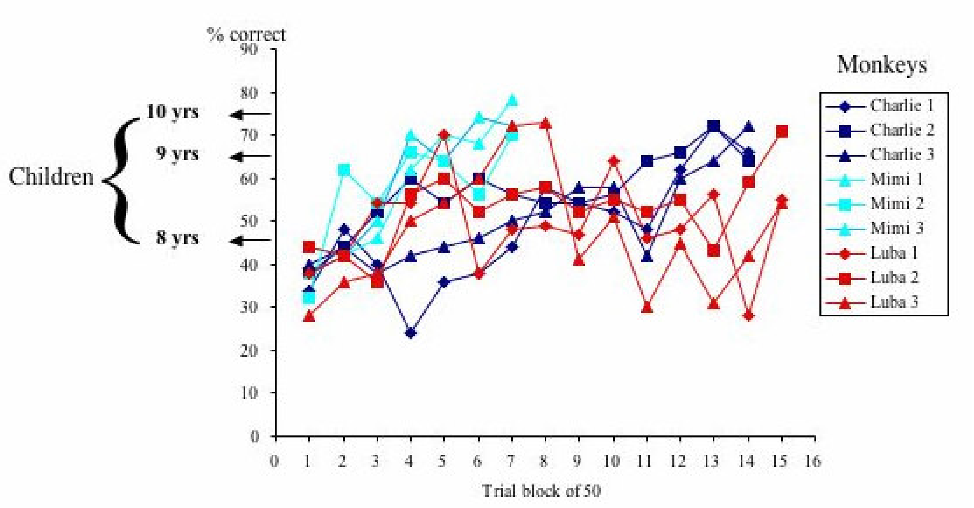

Figure 7. Individual learning curves for each of the three shape categories learned by *Cebus* during 9 item seriation where all monkeys achieved a criterion of 60% or above across all three categories within 50 consecutive trials. For comparison, the ordinate displays the level of 'spontaneous' seriation success by children of different ages using the same stimuli, depicted as a percentage of errorless sequences obtained over the course of 10 trials.

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[1] A cognate finding in this context by Brannon and Terrace (1998), using a number-based code with Rhesus macaques finds ordering of numerosities, but without a requirement to seriate all items explicitly: instead overlapping sets of stimuli (1-5 and 4-9) were first seriated in this study, followed by binary tests of the sort we first gave in our transitivity studies with squirrel monkeys (McGonigle & Chalmers, 1977). As we have argued, such transfer profiles even when accompanied by reaction time measures showing an SDE (McGonigle & Chalmers, 1986, 1992) can lead to an overestimate of the degree of linear representation in the series as a whole. The only way to be sure is to have all items seriated explicitly as the *Cebus* have done in the experiment just described.

Categorical and Hierarchical Control in Monkeys

Whereas we have shown impressive control of linear size sequences by monkeys, it remains the case that, as in human language, flexibility and productivity comes from hierarchical control. As assessed by classification and grouping behaviors, in human development the trajectory of such attainment suggests many stages of approximation to these structures. Spontaneous behavior-based classification by young children shows considerable development in the degree of sustained organization across their collections as a whole, moving from local small-group acts of classification to more planned collections that are controlled by identifiable dimensions of similarity and difference (Inhelder & Piaget, 1964; Vygotsky, 1962). The number and type of classes that children can achieve within a single act of grouping also seems to change from first-order classifying based on comparisons of similarity relations between individual elements within a single category only (Poti, Langer, Savage-Rumbaugh, & Brakke, 1990) to multiple classification based on disjoint categories that do not share any common features, and subsequently to reciprocal categories that do. The latter case, where for example a blue square belongs to one collection whereas a blue circle belongs to another, demands a sorting principle based on hierarchical control where one dimension of difference is nested within another. It is this hierarchical ability that ostensibly supports later class inclusion abilities, as revealed by linguistic tests of the sort given by Piaget during sorting tasks such as “Are there more circles or more blue ones?" (Inhelder & Piaget, 1964, p. 60).

As for nonhumans, the ability of subjects to categorize and segment in these terms seems impoverished, at least as revealed by the traditional sorts of free classification tests based on free play, and using measures such as the rate (number of object groups per minute), size (number of objects in groups), containment relations, spatial correspondence, and order of selection (Poti et al., 1990). Even chimpanzees seem to exhibit no more than two categories using such methods (Spinozzi, Natale, Langer, & Brakke, 1999), and then only from a disjoint condition in which objects belonging to different classes did not share any property. In the light of these results, the authors conclude that hierarchically integrated classification does not seem to be an option for chimpanzees (Spinozzi et al., 1999, p. 169).[2]

However, tasks given to nonhuman primates have often been of the short, snapshot variety using spontaneous behaviors; whereas the trajectory in human development for such behavior ranges over six years or more. So part of our long-

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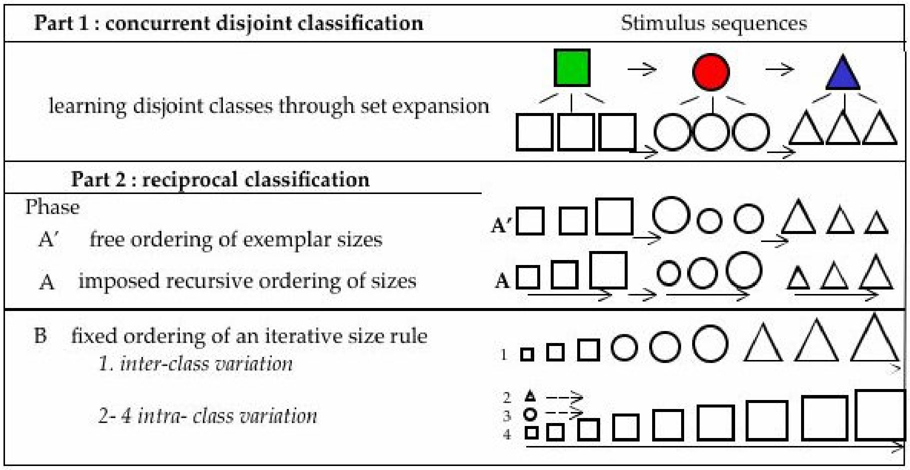
[2] Other forms such as oddity and same/different (e.g., Giurfa, 2001) operate with a much lower level of control. As Kinsbourne (1967) has shown with rats (an experiment in which the first author was an adviser), rats learn to discriminate stripes in mirror image oblique orientations in a ‘same-different’ task even though they cannot *identify* obliques when required to do so using conventional discrimination procedures. In eschewing specific identification requirements, the same-different task can be solved with simple (non-conceptual) codes demanding, at minimum, the detection of a difference (any difference) between discriminanda. Failure to detect a difference is ‘same’ by default. The first author has successfully implemented such procedures in visual discrimination of striped objects by robots (McGonigle, 2001).

term training objective with *Cebus* was to assess their ability for classification under explicit conditions of training, and where there are real incentives to classify. A second objective was to assess the utility value of any classification found with these methods. Would classification aid executive control by making it more efficient? The design of the study is illustrated in Figure 8.

Two forms of classification were used. The first condition required monkeys to sort items into three disjoint classes, each comprising identical exemplars within each class, and with no common elements across classes. In the second, sorting into three reciprocal classes was required, where exemplars of each class shared a common dimension of difference (size). In Part 1, the disjoint condition, each monkey was allocated a core sequence of three shapes that were to serve as prototypes for each of three categories. Following 3-shape sequence learning with three items, the sequences were subsequently expanded by progressively increasing the number of exemplars within each shape category—first to two exemplars, then to three. In Part 2, the reciprocal condition, the elements all varied by size within each class. At first, monkeys were first free to choose any order they liked within categories so long as they did not reiterate choices to any exemplar within a particular category. In the second phase of the reciprocal condition—an imposed recursive ordering of size—monkeys were forced to comply with the same size seriation rule within each category. In the final phase of Part 2, all monkeys were trained to sequence nine sizes, each within three different categories. This is the 9-item linear size seriation condition described earlier. This, however, was run concurrently, within training sessions, along with a condition also featuring nine sizes, but segmented into three categories.



The three strata of the experiment as summarized above show a disjoint classification phase (Part 1) that has hierarchical features by dint of the serial requirements of the task (which involves a branching procedure). Part 2 (Phase A) is explicitly hierarchical as it features inter-class exemplar overlap. In the final phase (Part 2, Phase B), linear size seriation with a series segmented by shape differences (1) is trained concurrently with three linear size series (2-4)

Figure 8. The design of the classification and seriation touchscreen study with *Cebus apella.*

In all phases monkeys were trained to a criterion of not less than 75 % correct across 20 consecutive trials. The results were clear and unambiguous. First, all subjects (four females were withdrawn from the final phases for breeding purposes) learned all sequences and all conditions of the study on which they were tested. These results are summarized in Figure 9.

Furthermore, performance on all phases indicated the use of a self-generated rule operating above the level of a finite-state device entrained through simple associations. This argument follows because it is quite impossible to explicitly train a sequence to identical items in the context of the conditions we report; instead, the subject must discover circumstantially that all identical items must be selected before ordering the remaining categorical items. This is an indication of an embedded ordering deemed as hierarchical by Lashley (1951) and Hulse (2002). In the disjoint condition, for example, where all categorical items were identical, there were no stimulus features that could signal or trigger a search for the next item. In short, whereas (icon) A may entrain B in an arbitrary sequence, A may or may not necessarily entrain the choice of B in a disjoint condition of this sort, depending on the subject's own monitoring of what has been selected already. Thus A1 entrains A2; and A2 entrains A3; however only A3 entrains B1. This makes the stimulus (of sorts) for A-B under these circumstances essentially a self-produced one of AAA-B.

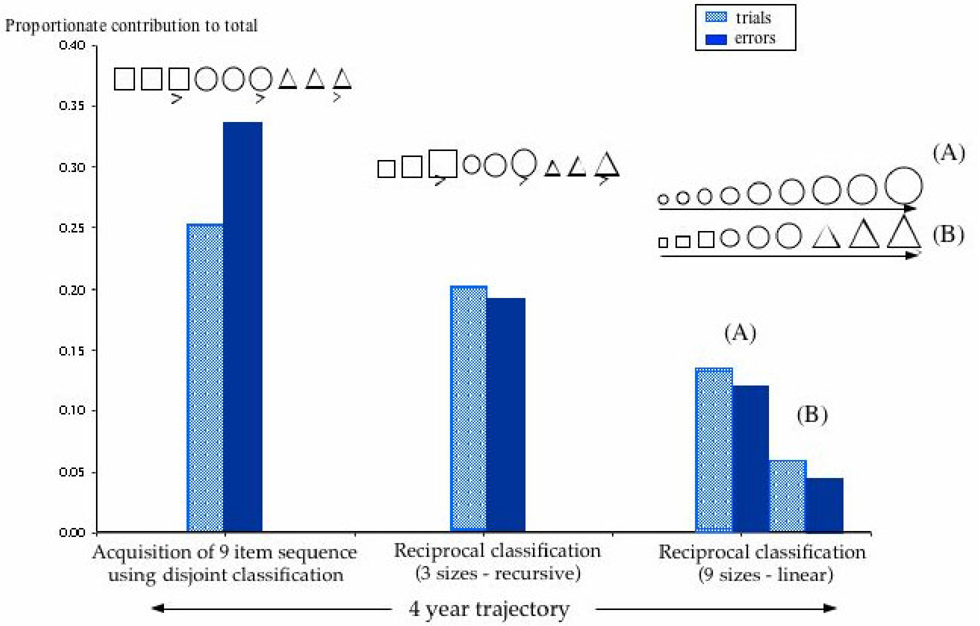


Figure 9. Performance by *Cebus apella* on linear and hierarchical sequences expressed as relative effort.

So the disjoint condition can only be solved by a categorization procedure where all exemplars of the first category in the sequence must take priority over all those from the second category, and so forth. How this is done is suggested by the error profile recorded when monkeys switch from 2-exemplar to 3-exemplar conditions. As Figure 10 shows, the basis for the exit strategy within a particular class may be based on counting, for the initial transition from a 2-exemplar to a 3-

exemplar test reveals a strong tendency to exit a category search prematurely after 2 exemplars, even though a third exemplar is clearly visible.

Strong evidence for further hierarchical organization comes from the reciprocal condition. On classifier criteria alone, reciprocal classification requires hierarchical analysis where an element is both a member of a class and the class is part of a series. In the reciprocal classification task, constituents are both equivalent and different, and in that sense have the hierarchical organization sought by Piaget in his classification tests (Inhelder & Piaget, 1964). Monkeys not only learned orders constructed in this way, they did so relatively easier than the one-level disjoint condition, as Figure 10 illustrates. Finally, in the 9-item linear seriation phase, performance was significantly improved when the series was segmented (formally) into classes (Figure 10). Yet in this condition, the subjects had the option of ignoring the categories altogether as size alone was necessary (and sufficient) for the solution. This result therefore suggests that classes were also psychologically real for *Cebus* and supported a spontaneous hierarchical role in the seriation.

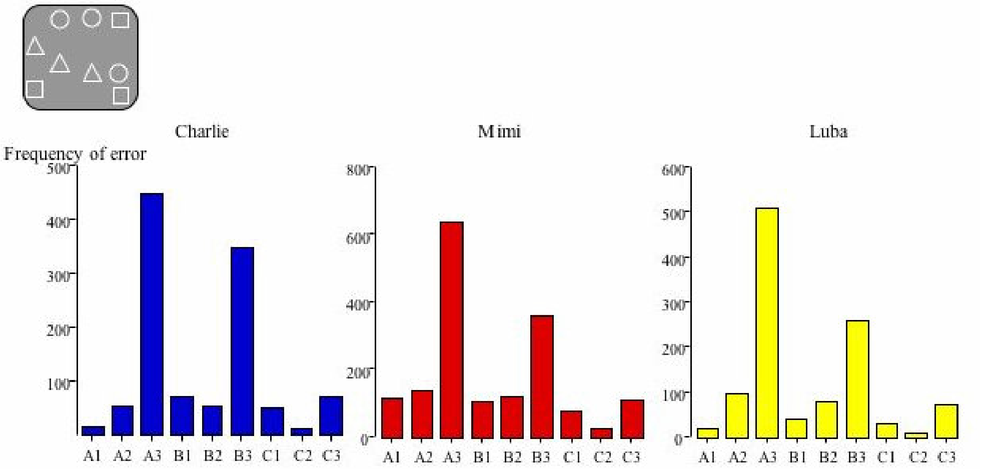


Figure 10. Individual error distributions from three *Cebus* during the transition from 2 exemplars per class to 3 exemplars per class within the disjoint classification phase.

Classification and Productivity in Nonhumans

So here we have four new sources of cognitive information re the status of nonhuman primates. First, contrary to claims based on free sorting techniques (Tomasello & Call, 1997), nonhumans can sort into three categories concurrently, even when the categories are related through similarities in class membership. Second, sequences are operated hierarchically in both conditions, contrary to oft-repeated claims that nonhumans show no evidence of hierarchical organization—at least of the productive and flexible sort of sequences that might enable the emergence of language from broad-band competences adapted for quite different roles (Christiansen and Kirby 2003; Conway & Christiansen 2001). Here, our results are in line with a recent report by Bergman and Beehner (2003) showing that baboons classify others simultaneously both according to rank and kinship. Third, the results from the recursive conditions successfully complied with by *Cebus apella* indicate that recursion itself is not a necessarily a unique feature of narrow-band linguistic competence as argued by Hauser et al. (2002). Fourth, the categories provided appear to have utility as segmentation devices enabling more effective executive control of highly demanding series suggesting non-human primate competence for hierarchical organization. As Hauser and McDermott (2003) recently acknowledge, our results (McGonigle et al., 2003) may stand as a possible exception to the generalization that infinite productivity is uniquely a human ability. Certainly the learning trajectory we document in the most extensive, longitudinal monkey study on record (and possibly for any species, including humans), indicates considerable momentum (Fischer et al., 2000) in the manner in which monkeys adapt to tasks of progressive difficulty (both in qualitative as well as quantitative terms) achieving at terminus, the most impressive seriation performance ever shown by a nonhuman subject. This is illustrated in Figure 9, which records the basic benchmarks of achievement over the entire course of the study, computed as the relative cost of each of the major training phases and shows that monkeys accelerate in their problem solving efficiency, coping progressively better with later, more difficult problems. In short, the productive control by monkey was not only evinced in the separate stages of this study but over the course of the investigation as a whole.

Learning and Epigenesis

Children in the lab are supported by rich environments at home, where strong cultural and pedagogic pressures favor specific teaching and learning program for the child. In contrast, even our simians in the current study received no more that one hour of formal instruction per day. The rest of their time was spent in the colony rooms—hardly overtraining when compared to the human context. Moreover, if Bates (1991) and others are correct in their view that children learn language as a result of exposure to rich environmental stimulation, recruiting cognitive abilities in so doing that are not necessarily language specific and taking some years to do so, the gap between human and nonhuman is colossal, both in terms of the task ecology and the scale of the learning program. As a consequence, we would agree with the conclusions of Fitch, Hauser and Chomsky (2005) in a recent refutation of claims for the uniqueness of human language, as advanced by Pinker and Jackendoff (2005), when they say that "claims of human uniqueness must not be made in the absence of any relevant animal data" (Fitch et al., 2005, p. 195). Nevertheless, a tradition of impoverished learning studies with animals has robbed comparative psychology of a crucial role in this context.

To break the mold, a first key step in considering the extent to which the epigenesis of human achievements has its origins in pre-human evolution is to establish the qualifying behaviors. To our knowledge, no nonhuman has ever before sorted objects into multiple categories, or executed serial ordering with the level of control we report here. With the monkey, therefore, a first discovery is the behavior itself. As for its interpretation, the convergent profile of child and simian performance under similar conditions of testing permits a number of new hypothesis concerning the genesis of the mechanisms responsible. First, slow to progress to the successful sequencing of long strings for both species, it would seem a case more of honest toil than the product of insight or structural revision, of continuous rather than saltatory change both in monkeys and humans. Like the child, monkeys needed no perceptual template or the need to operate under conditions of what Piaget (1973) described as contingent classification—where the sorting or seriating of actual objects by the child changes the state of the test array, a visible and cumulative consequence of the sort procedure. With our techniques, by contrast, no such consequences are available. However, this is not to say that such externalizable consequences of action have no role in the epigenesis of ordering. On the contrary, where the actions of the subject when seriating can affect what the test series looks like, a form of externalization is created which brings with it several advantages. The first is a memory one, where a series can be viewed as an exogram and extended and repaired at leisure. A series executed on the touchscreen under the conditions as we describe here, by contrast, gives no such feedback, placing instead a large burden on working memory offset only by the application of iterative size rules and or segmentation procedures based on categories alone. When externalized, moreover, such a series can be counted. Access to this sort of device is precisely what may lead to the further developments in seriation we describe earlier–first in terms of a possible acceleration within the core executive skill of monotonic search, and subsequently as the ability to deal with nonmonotonicity by using the number line (a cultural device itself from monotonic organization). Finally, the ability to externalize cognitive products may alter the intended goal of a production into a state rather than a procedure and give the subject an image of achievement that can be shared with others. For simians, the lack of manipulative skills required to construct series in the first place may turn out to be a serious block on their further cognitive development (Tallis, 2003). However with new paradigms we can create conditions enabling monkeys to view their cognitive procedures as externalized arrays, without requiring a prior lexical process as suggested by Donald (1977), such as a collection of icons formed at the base of the touchscreen, contingent on icon selection. With these techniques, we are now in a position to evaluate whether a new cycle of causality might be created (McGonigle & Chalmers, 2001) whereby cognitive systems are scaffolded to new heights of achievement, through externalization.

In conclusion, our program has been focused on those adaptive cognitive competences (McGonigle & Chalmers, 2006) that appear to be immediate precursors of runaway developments in the human, alert to the contribution made by long term learning itself to the emergence of high level cognitive skills. Whereas there may be numerous gradations between nonhumans and men (Darwin, 1874) there are also many gradations between the young, the mature and the enculturated human. Within a common agenda, an important comparative goal of this program has been to clarify these gradations. An important goal for the future will be to specify the extent to which these are consequences of nurture and culture as they are of biological inheritance.

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