Origins of Numerical Concepts: A Comparative Study of Human Infants and Nonhuman Primates

by

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Abstract

The question of numerical representations in humans has given rise to speculations of whether human number faculty is fundamentally tied to human linguistic capacity. Two ways of addressing the question of the relationship between the human numerical system and the uniquely human language faculty is by investigating what the numerical representations of prelinguistic human infants are and by asking whether nonhuman primates show comparable capacities. This thesis presents data on the precursors to numerical representations in young infants and nonhuman primates, rhesus macaques (*Macaca mulatta*) and cotton-top tamarins (*Saguinus œdipus œdipus*). Research was conducted in the Infant Cognition Laboratory at the Department of Brain and Cognitive Sciences at MIT, at the Primate Cognitive Neuroscience Laboratory at Harvard University and at the Caribbean Primate Research Station in Cayo Santiago, Puerto Rico.

Chapter II investigates the nature of the representations underlying numerical knowledge of prelinguistic infants. Evidence in the infant literature using the preferential looking and violation of expectancy technique has shown that prelinguistic infants possess sophisticated numerical knowledge. Young infants can represent small numerosities of entities such as objects, sounds and events, presented in visual or auditory arrays. However, it is not clear which mechanism might be subserving this capacity. Three addition experiments were conducted with 8- and 10-month olds to show that young infants represent the number of objects in visual arrays and that this prelinguistic numerical capacity is fundamentally tied to the construction of object files in memory.

Chapter III proposes to investigate nonhuman primates using the same methodology used with human infants to show whether these prelinguistic capacities are uniquely human or whether they can be found in nonlinguistic related species. Six addition studies were conducted with rhesus macaques and cotton-top tamarins to investigate whether they would be able to represent small numerosities. The results show that rhesus macaques and cotton-top tamarins present spontaneous numerical abilities comparable to human infants. These spontaneously available numerical representations, thus, do not embody a uniquely human capacity.

Chapter IV explores the question of the construction of object kinds and the criteria nonhuman primates use for object individuation. A study was performed on semi-free-ranging rhesus macaques to show that monkeys, unlike young human infants, individuate objects on the basis of property/kind information. The capacity to construct objects kinds, thus, may not necessarily be uniquely human.

Thesis Supervisor: Susan Carey, Professor of Brain and Cognitive Sciences

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Humanity has in the course of time had to endure from the hands of science two great outrages upon its naive self-love. The first was when it realized that our earth was not the centre of the universe, but only a speck in a world-system of a magnitude hardly conceivable. The second was when biological research robbed man of his particular privilege of having been specially created, and relegated him to a descent from the animal world.

S Freud

It is, therefore, highly probable that with mankind, the intellectual faculties have been mainly and gradually perfected through natural selection... Undoubtedly, it would be interesting to trace the development of each separate faculty from the state in which it exists in lower animals to that which exists in man.

C Darwin

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Chapter I

In mathematics, the art of asking questions is more valuable than solving problems.

G Cantor (1867)

Introduction

Investigations in the domain of number under a psychological perspective have undergone substantial transformations at least for the last thirty years. The domain of number is of particular interest because of its nature. Number is an abstract concept, an abstract descriptor for sets of objects which are apprehended in the world. It has been characterized as uniquely human, and intrinsically related to the human linguistic faculty (Chomsky, 1988). Because of its abstract nature, researchers in the animal field have been skeptical to attribute numerical representations to nonhuman creatures (see Rilling, 1993 for an extensive review on the animal literature on number).

More recently, however, Gallistel (1990) has proposed that the capacity for number should be understood as a basic process, and has shown that there is a fair amount of evidence in the literature that animals can be trained to discriminate and assign number. An advocate of domain-specific cognition, Gallistel stands on the side of researchers who posit that animal, as well as human, cognitive architecture is characterized by domain-specific mechanisms (Gallistel, Brown, Carey, Gelman & Keil, 1993). Specifically regarding human cognition, the general idea is that knowledge of the world is divided into different content areas or cognitive domains (Baillargeon, 1995; Carey & Spelke, 1994; Carey, 1995; Leslie, 1994; Spelke, Breinlinger, Macomber & Jacobson, 1992). These domains are organized according to different theoretical frameworks, which constitute lay understandings of different areas of knowledge, e. g., language, number, intuitive mechanics, and so forth.

The domain of number is of particular interest, under the psychological viewpoint, for the exploration of the mental processes involved in number comprehension and production. Investigations in the animal field (see Davis & Pérusse, 1988 and Gallistel, 1990, for extensive reviews of numerical capacities in animals) and in the human field, both in adult cognition and cognitive development (Gallistel & Gelman, 1992; Gelman & Gallistel, 1978; Wynn, 1990, 1992) show that the domain of number embodies a variety of processes.

Research in human developmental psychology has shown that very young infants present rudimentary capacities involving small numerosities. Habituation studies in the 80s and 90s established that young infants are sensitive to numerical variances. The main objective of this research has been to investigate whether infants have a capacity to discriminate small numerosities from 2 to 4 objects (Starkey & Cooper, 1980; Strauss & Curtis, 1981; Antell & Keating, 1983; Treiber & Wilcox, 1984; Starkey, Spelke & Gelman, 1990, 1991; van Loosbroek & Smitsman, 1990; Tan & Bryant, 1996). Habituation trials are presented to the infants in which they are shown a series of slides, which contain a constant number of items. Looking times to these presentations are recorded. When a determined criterion is met (e.g., looking times decrease to 1/2 the time of first two consecutive trials), the infants receive test trials comprised either of trials with the same number of items as in the habituation period or trials with a new number of items. If the infants discriminate the numerosities, they will look longer at the displays with the different numerosity than at the displays with the numerosity they were habituated to. With rare exceptions, young infants are able to discriminate between 2 and 3 items (dots, familiar objects), sometimes up to 4, but not larger numerosities of items (4-5, 4-6).

Wynn (1992) followed this research with evidence that young human babies not only discriminate numerosities on the basis of a perceptual awareness of number of objects presented in a visual array, but they also represent the numerical relations among sets of one, two and three objects. The studies utilized the preferential looking/violation of expectancy method. Simply put, prelinguistic infants, when shown "tricks" that violate predictions generated by their current representational capacities, look longer at the outcomes of such tricks than at those outcomes that accord with their representational system. For example, if I show babies two puppets being placed into a box, they stare longer if they see only one puppet when the box is opened than if they see two. In Wynn (1992), infants were presented an open stage, into which a Mickey Mouse doll was placed. A screen was then placed to hide the interior of the stage and the Mickey Mouse. Subsequently, a second Mickey Mouse doll was added behind the screen. When the screen was removed, the infants either saw an expected outcome (two objects) or an unexpected outcome (one object or three objects). This addition task can be dubbed a 1 + 1 = 2 versus 1 experiment, namely, infants saw 1 object being added to 1 object to yield the expected outcome of 2 objects or the unexpected outcome of 1 object. Wynn also carried out an addition 1 + 1 = 2 or 3 and a subtraction 2 - 1 = 1 or 2 version of this experiment to address the question of whether the infants would represent the exact number of objects. The results show that 5-month-old infants spontaneously represent the numerosity of small sets of objects. These results also show that young infants distinguish two numerically distinct objects (though physically identical) from one and three objects.

Wynn (1996) provides further evidence in support of infants' capacity to determine number of entities. She habituated 6-month-olds with a puppet either jumping three or two times. In the test trials, she then presented the infants with the doll jumping two or three times. The infants who were habituated to three jumps looked longer at the two-jump doll event, whereas the infants who were habituated to two jumps looked longer at the three-jump doll event. This result indicates that the infants individuated the jumps and enumerated them. Therefore, it seems that infants are not only able to tell number of objects, but can also generalize this capacity to tell number of events that exist only in time, such as jumps of a doll. Although all these studies show a variety of different abilities in different manipulations, a mechanism to account for the representations underlying these abilities has not yet been successfully presented and is subject of much debate. It has been suggested that subitizing, an accurate capacity to discriminate (or estimate) numerosities visually presented, observed in human adults, would be the process by which infants succeed in such tasks (Trick & Pylyshyn, 1994). It has also been suggested that an accumulator-type of mechanism, originally proposed to account for animal counting (Meck & Church, 1983) would be the mechanism subserving human infant capacities.

Despite the so far uncertain nature of these abilities, the infant studies on number seem to argue that there exists in human beings a natural, automatic, spontaneous capacity to represent number of objects. This ability is very consistently shown in different manipulations of the preferential looking and violation of expectation paradigm. Why would infants present this unique spontaneous numerical capacity? One possibility is that rudimentary numerical knowledge underlies the human number faculty and that language has a major role in providing the environment for the development of numerical representations. It has been argued that the number faculty is related to the human linguistic faculty (Chomsky, 1988). According to this view, the number faculty depends upon the language faculty. An essential aspect of human numerical system is the property of discrete infinity. That is, humans can generate an infinite quantity of numbers on the basis of adding one to the first fundamental numerosity <u>one</u> ad infinitum. Chomsky proposes that this property can only emerge from a generative system such as the one that underlies human language. The generativity of language can be characterized as the infinite use of finite means -- that is, language provides a finite number of elements and rules for combining them (Chomsky, 1980). This allows humans to generate an infinite combination of sentences. The human numerical system is thus characterized by this same type of generativity.

It is true that number is fundamental in the grammar of languages. Numerical concepts are picked out by quantifiers such as "one", "a" and "another". Number can be marked in nouns and verbs, usually denoting the distinction singular/plural. Concepts such as one and two are part of the human language faculty because they underlie the concepts of "one" and "another". The concept of one is obligatorily marked in the syntax of languages. Every time we use count nouns, a numerical concept is implicitly expressed. If these concepts are automatically grammaticized in language, then, by virtue of the fact that humans possess language, it may be that they are spontaneously available. It is possible that an automatic representation of number in language (i.e., one is the fundamental notion of our numerical system; from one you can generate the whole infinite number system) might allow human beings to spontaneously represent number and ultimately construct a symbolic numeron-type of representation.

A possible test of the hypothesis that language provides the favorable environment for the existence of numerical capacities is to investigate nonlinguistic creatures. There is a vast literature on animal numerical capabilities (dolphin: Mitchell, Yao, Sherman & O'Regan, 1985; parrot: Pepperberg, 1987; raccoon: Davis, 1984; rats: Capaldi & Miller, 1988; Meck & Church, 1983; birds; Pastore, 1961; Koehler, 1950; Honig & Stewart, 1989; see also Gallistel, 1990 and Davis & Pérusse, 1988, for an extensive review of this literature). For example, rats and pigeons can learn to discriminate number of responses of numerosities up to 24 (rats) and 50 (pigeons) in tasks utilizing the operant conditioning technique (Capaldi & Miller, 1988; Rilling & McDiarmid, 1965). Monkeys have been shown to learn to discriminate paired numbers of stimuli (Douglas & Whitty, 1941; Hicks, 1956; Kuroda, 1931; Thomas & Chase, 1980) and tell the ordinal relationships among them (Washburn & Rumbaugh, 1991). Lastly, various species of animals have been studied as single cases and have been shown to be trained to discriminate numerosities (a dolphin: Mitchell, Yao, Sherman & O'Regan, 1985; a raccoon: Davis, 1984) and count (a parrot: Pepperberg, 1987). All these studies suggest that different types of numerical representations seem to be present in various different species. However, none of them provide evidence that these representations are comparable to those of humans.

The number literature on chimpanzees, on the other hand, gets closer to a characterization of learned capacities that may be more comparable to those of humans. Studies in the psychological literature on chimpanzees' capacities have proliferated for at least 60 years. At first, it was believed that chimpanzees were putatively the smartest nonhuman primate species, and that investigating such a species would allow researchers to find correlates between their capabilities and our own (Ferster, 1964). More recently, with the advent of genetic research, chimpanzees have been shown to be the closest related species to humans, sharing with us 95% of their genetic code (Sibley & Ahlquist, 1984). It seems, thus, that putative intelligence and phylogenetic proximity have impelled a vast amount of research with chimpanzees, addressing questions which range from linguistic abilities (Gardner & Gardner, 1969, 1975; Premack, 1970; Savage-Rumbaugh, Rumbaugh & Boysen, 1980; Terrace, Pettito, Sanders & Bever, 1979), theory of mind (Woodruff & Premack, 1981), to numerical abilities (Boysen, 1993; Matsuzawa, 1985; Washburn & Rumbaugh, 1991), in the realm of cognitive research.

Chimpanzees can be taught to discriminate proportionality of quantities (Woodruff & Premack, 1981); to match numerosities from 1 to 7 on the basis of binary numbers (Ferster, 1964); to assign symbolic tags for numerosities from 1 to 6 (Boysen, 1993; Boysen & Berntson, 1989); to sum across grouping on the basis of more and less (Pérusse & Rumbaugh, 1990; Rumbaugh, Savage-Rumbaugh & Hegel, 1987; Rumbaugh, Savage-Rumbaugh & Pate, 1988); to count and add numerosities from 1 to 9 (Matsuzawa, 1985; Matsuzawa, Itakura, & Tomonaga, 1991). Sheba (Boysen, 1993), for example, has reached a stage where she seemingly has a limited numeron system. Her numerical system may be characterized as a limited numeron system because she knows symbols that correspond to each different numerosity. Much the same way children learn that /wun/ corresponds to one, Sheba has learned that "1" corresponds to one, "2" to two, etc. In this respect, the numerical knowledge of this chimpanzee is largely comparable to that of a 3 year old human child.

What differs, however, is that the chimpanzees are not likely to ever spontaneously generalize what number comes next in the counting list. There is no evidence that the chimpanzees reach an understanding that there can be more numbers generated after the number just learned. There is no evidence that the chimpanzees will ever learn the list of numbers that 3 1/2 year old human children learn so quickly once they realize how the system works. Therefore, there is no evidence that the system of these animals is generative and can produce an infinite number of symbols.

Another difference between the chimpanzees' and the human children's developing numerical capacities is that it is extremely hard for chimps to learn the numerical system in which symbols stand for the numerosities counted. That is, the chimpanzees need to go through an extensive amount of training before reaching the stage in which they know the right numerical assignment. Sheba, for example, the "brightest" of all chimpanzees ever tested, learned the mapping between numerical symbol and numerosity over a period of two years! (Boysen, 1993). It was required that she undergo multiple sessions of numerous trials per day. Along the process, the number of sessions could vary from 4 to 12, in which the number of trials could vary from 20 to 975. Thus, it seems that the chimpanzee's capacity for number depends on the long and hard process of training.

Thus, the evidence from the literature on number with nonhuman primates show that it is necessary that the animals undergo <u>extensive training</u> to get at a numerical representation. It is possible that nonhuman primates also present spontaneous automatic numerical representations, just as prelinguistic human infants do. However, these studies do not provide evidence for spontaneous representations of number in nonhuman primates. The evidence from habituation and addition experiments show that prelinguistic human infants represent sets of 1, 2 and 3 objects in the absence of language. It is clear that humans' spontaneous numerical capacity ultimately gets linked with the linguistic system, in which numerical concepts are linguistically expressed. These considerations lead to two hypotheses. If spontaneous numerical representations are only available to humans, then it is possible that number is fundamentally tied to the human language faculty, being a by-product of the uniquely human linguistic capacity. Alternatively, if nonhuman primates are shown to present comparable spontaneous numerical capacities, just as the ones shown with human infants, then it may be that the number faculty is more fundamental than hypothesized, thus not being a product of the uniquely human linguistic system.

This thesis is composed of three sets of studies. Chapter II composes an article submitted for publication to the journal *Cognitive Development*.. It investigates in more detail the nature of the representations underlying the spontaneous numerical knowledge of prelinguistic human infants. Chapter III proposes a new approach to the comparative cognitive research in which spontaneous cognitive primitives, such as number, can be investigated with the use of the preferential looking and violation of expectancy technique. Chapter IV explores the question of the construction of object kinds and the criteria nonhuman primates use for object individuation and numerical identity.

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Chapter II

What representations might underlie infant numerical knowledge

Introduction

Simple habituation experiments provide ample evidence that young infants, even neonates, are sensitive to numerical distinctions among sets of one, two and three entities (e.g., dots: Starkey & Cooper, 1980; Antell & Keating, 1983; familiar objects: Strauss & Curtis, 1981; continuously moving figures: van Loosbroek & Smitsman, 1990). For example, infants who are habituated to pictures of sets of two familiar objects varying in type, size, and position, dishabituate when presented with arrays of one object or three objects (Strauss & Curtis, 1981). Further, using the methodology of violation of expectancy, Wynn (1992) showed that 5 month-old infants represent the numerical relations between one, two, and three objects. For example, when shown one object placed on a stage, covered with a screen, and then another object introduced behind the screen, infants expected precisely two objects, and looked longer at unexpected outcomes of either one object or three objects than at the expected outcome of two objects when the screen was removed (Wynn, 1992; see Simon, Hespos & Rochat, 1995, for a replication).

These results leave open the nature of the representations underlying infants' performance. What these representations might be, and the senses in which they may or may not be "genuinely numerical", is a source of intense debate. Some have claimed that infants' capacities in the habituation studies reflect subitizing, as opposed to counting, and are thereby less than fully numerical (Starkey & Cooper, 1980; Strauss & Curtis, 1981); however, such an argument requires accepting that representations of one, two and three established by a subitization process are not numerical (see Gallistel & Gelman, 1992, for a lucid discussion of this issue). Further, if subitization is a process that operates only upon a visual array, then the infant addition and subtraction studies (Wynn, 1992; Simon et al., 1995; Koechlin, Dehaene & Mehler, under review) rule out subitization as the sole basis of infants' performance, for in these studies infants represented two entities even though they had not seen two entities together in a visual array.

Others have raised the possibility that success on the Wynn (1992) addition and subtraction tasks does not reflect numerical knowledge at all, but rather, it reflects already well documented physical reasoning abilities (e.g., Simon, et al., 1995). Many studies have established that infants of 5 months and even younger establish representations of an object presented in a stage and can reason about the existence of and physical interactions between objects that are hidden behind screens (Wynn, 1992; Spelke, Kestenbaum, Simons & Wein, 1995; Spelke & Van de Walle, 1995; Baillargeon, 1995). The idea here is that infants build a model of the objects behind the screen, and update this model whenever objects are introduced or removed. Longer looking times to unexpected outcomes reflect mismatches of the model constructed of the objects in the array and the array revealed when the screen is lowered.

Simon et al. (1995) ultimately argue against this physical reasoning account of infants' success on the Wynn addition studies, on the grounds that infants are not affected by physical mismatches between the mental model and the revealed array <u>unless</u> those mismatches are also numerical. That is, if an Ernie doll is introduced behind the screen, and then an Elmo doll is added, the infant pays more attention to the numerically unexpected outcomes of just one doll, but not to outcomes of two Ernies or two Elmos, even though these outcomes are physically unexpected. However, as Simon et al. note, these data are not conclusive, for they depend upon what criteria the infants use for numerical identity. For instance, the infants' models may be of two <u>objects</u> behind the screen. In other words, the property differences between Ernie and Elmo may not enter into the infant's judgments of "how many." Xu and Carey (1996) argued that infants use only spatiotemporal criteria to individuate objects, as opposed to kind or property information, as late as age 12 months. Finally, it is not clear that the physical reasoning model is not numerical, for such a model must include criteria for numerical identity (sameness in the sense of same one; the baby needs methods for distinguishing between one object seen on different occasions from two numerically distinct objects) and the comparison process between models must be sensitive to one-one correspondences of individuals.

In order to establish whether infants' capacities are "genuinely numerical", it is necessary to distinguish classes of models that may underlie performance, attempt to bring data to bear on the question of which, if any, underlies infant performance, and only then ask the senses in which the representations are or are not "genuinely numerical". We know of three serious proposals for infant representation that could account for their successes in the studies cited above:

The numeron list proposal (Gelman & Gallistel, 1978). Gelman and Gallistel proposed that infants establish numerical representations through a counting procedure that works as follows. There is an innate mentally represented list of symbols called "numerons": !, @, *, $, % ... (Of course, we do not know what such symbols might actually be). Entities to be counted are put in one-to-one correspondence with items on this list, always proceeding in the same order through the list. The number of items in the set being counted is represented by the last item on the list reached, its numerical value determined by the ordinal position of that item in the list. For example, in the above list, "@" represents 2, because "@" is the second item in the list.

The accumulator proposal (Meck & Church, 1983). Meck and Church proposed that animals represent number with a magnitude that is an analog of number. The idea is simple -- suppose that the nervous system has the equivalent of a pulse generator that generates activity at a constant rate, and a gate that can open to allow energy through to an accumulator that registers how much has been let through. When the animal is in a counting mode, the gate is opened for a fixed amount of time (say 200 ms) for each item to be counted. The total energy accumulated will then be an analog representation of number. This system works as if length were used to represent number, i.e., "–" being a representation of 1, "—" a representation of 2, and so on (see Gallistel, 1990 for a summary of evidence for the accumulator model).

<u>The object file model</u> (First order logic instantiation). Just as Simon et al. (1995) suggested, babies may be establishing a mental model of the objects in the array. That is, they may be constructing an imagistic representation of the stage floor, the screen and the objects behind the screen, creating one object-file (Kahneman & Treisman, 1984) for each object behind the screen. Such a model represents number in virtue of being an instantiation of the following: $(\exists x)(\exists y)((\mathrm{object}(x)\ \&\ \mathrm{object}(y))\ \&\ x \neq y\ \&\ \forall z(\mathrm{object}(z) \rightarrow (z=x)\ \mathrm{V}\ (z=y)))$. In English, this states that there is an entity, and there is another entity numerically distinct from it, and that each entity is an object, and there is not any other entity. This sentence is logically equivalent to the sentence "There are two objects". Note that, in such a representation, there is no single symbol for 2 at all, not "@" nor "—" nor "2" nor any other.

These three proposals for nonlinguistic representational systems for number are genuinely different from each other. The first two (the numeron list model and the accumulator mechanism) embody distinct symbols for each integer. These differ in the nature of the symbols they use. In the accumulator model, an analog representational system exploits the fact that the symbols are magnitudes linearly related to the numbers they represent. In the numeron list model, in contrast, each symbol bears an arbitrary relation to the number it represents. And, as previously noted, in the object file system, there is no distinct symbol that represents each integer at all. In this model there is nothing that corresponds to counting in terms of a set of symbols, whether arbitrary (numerons) or analog (states of the accumulator). Thus, whereas the object file proposal <u>does</u> constitute a numerical representation, in the sense of requiring criteria for numerical identity and representing the distinctions between different numbers of entities, it is not a fully symbolic representation of number, having no unitary symbol for each integer, nor any distinct procedure of counting defined over its symbols. If the representations underlying infant success on number habituation and infant addition experiments are generated by processes that construct mental models of the individual objects in the arrays, these representations are numerical in a weaker sense than if they are generated by an accumulator mechanism or the numeron list model.

The three models differ as well in the process underlying discrepancy detection between the representation formed as objects are introduced (or removed from, in subtraction) behind the screen and the representation of the resultant display after the screen is removed. Take a 1+1 = 2 or 1 event as an example. On the two symbolic models, the results of two counts are compared -- the symbol for the number of objects resulting from the operations of adding and subtracting (e.g., "@" or "—") is compared to the symbol resulting from a count of the objects in the outcome array ("@" or "—" in possible outcomes or "!" or "–" in impossible outcomes). According to the object file proposal, a representation consisting of two object-files constructed during the addition portion of the event is compared to a representation of two object-files (possible outcome) or one object-file (impossible outcome) by a process that detects one-one correspondence between the object-files in the two representations.

If the object file proposal is correct, then experimental manipulations that would interfere with the construction of such models should hinder performance. Baillargeon, Miller and Constantino (1995) reported a suggestive result along these lines. They found that 10-month-old infants succeeded in a 2+1 = 3 or 2 addition experiment, but failed in a 1+1+1 = 3 or 2 addition experiment. Consider what is required to construct a mental model of three objects in each of these two situations. In the 2+1 = 3 or 2 condition, the infant is shown an empty stage upon which a screen is placed. The child constructs a model of an empty stage with a screen on it. Two objects are introduced, simultaneously, behind the screen. The child must update his or her model, mentally constructing a new model of two objects behind the screen. Then another object is introduced. The infant must again operate on his or her mental model, updating it by adding another object to it, producing a model of three objects behind the screen. Ten-month-olds succeed in this condition, looking longer at the unexpected outcome of two objects when the screen is removed than at the expected outcome of three objects.

Now consider the 1+1+1 = 3 or 2 condition. The infant is shown the empty stage and the screen is placed on it. As before, the infant must construct a model of the empty stage behind the screen. An object is placed behind the screen, and the child must operate on that model, updating it to create a mental model of one object on the stage behind the screen. Then a second object is placed behind the screen, and the infant must again operate on his or her mental model, updating it a second time to yield a model of two objects on the stage. Then a third object is placed behind the screen and the child must operate on the model again, updating it a third time, yielding a representation of three objects on the stage. On the assumption that each updating of a mental model in imagery yields a noisier representation, we can understand why a model of 1+1+1 objects (three updates) is harder for the child to construct than 2+1 objects (two updates). Note that on either the numeron list model or the accumulator model, in which a counter is incremented for each item to count, there is no natural explanation for why 1+1+1 is harder to compute than is 2+1.

In Wynn's (1992) original 1+1 addition experiment, the infants saw the first object placed on the stage, the screen was raised, and then the second object was introduced. They were habituated to this sequence of events. Only one update of a model constructed from visual contact with the object on the stage was required, and the babies were provided with many repetitions of the event in aid of the process of constructing an updated mental model of two objects behind the screen. Five-month-old infants succeeded on the task. Simon et al. (1995) did not habituate infants to the events; the infants saw only once an object placed on the stage, the screen placed in front of it, and the second object introduced before the screen was removed to reveal the outcomes. Again, 5-month-old infants succeeded. Thus, 5-month-olds succeed in tasks which require one update; 10-month-olds succeed in tasks which require two, but fail in a task which requires three. This analysis suggests that infants' capacity for constructing and updating mental models undergoes developmental change between ages 5 and 10 months. It also predicts that there will be an age between 5- and 10-months in which infants would succeed at tasks requiring one update but would fail at tasks requiring two updates. Experiment 1 tests this prediction.

Experiment 1

Wynn's (1992) procedure can be changed from one which requires one update of a model constructed on the basis of perception to one which requires two updates simply by changing when the screen is introduced. We dub Wynn's procedure "object-first" since the child sees the first object on the stage before the screen is placed in front of it. In a "screen-first" procedure, the child is shown an empty stage, a screen is introduced, and an object introduced behind it (first update of a model of the empty stage) and then a second object is introduced (requiring an update of the model constructed just before -- second update). We predict that there is an age at which infants will succeed in the object-first condition (replicating Wynn, 1992, and Simon et al., 1995) but will fail in the screen-first condition. Given 10-month-olds' sensitivity to the distinction between 2 updates and 3 updates in Baillargeon et al.'s (1995) data, 8-month-olds were chosen for Experiment 1.

The idea behind this experiment is that a model of an object actually seen on the stage is more robust than is a model constructed in imagery of an object on the stage, and that each new model created by operations in imagery is increasingly less robust. The object file proposal also suggests that infants may represent the exact location of the seen object on the stage (however, see Koechlin, Dehaene & Mehler, under review, for evidence that such location information is not necessary for success). In Wynn's (1992) study, the unexpected outcome of one object was created by removing the <u>second</u> (previously unseen) object, leaving the object that the infant had actually seen in the location in which the infant had actually seen it. If infants are representing the exact locations of the objects on the stage, then they may perform better on trials in which the unexpected outcome is due to the first object being removed, especially in the object-first condition, where the first object is actually seen on the stage.

Method

Participants

Sixty-four full-term 8-month-old infants (32 boys, 32 girls) ranging in age from 7 months and 11 days to 8 months and 25 days ($\underline{M}_{age}$: 8 months and 8 days) were tested. Thirty-six additional infants were excluded because of fussiness (29), experimenter error (4), equipment failure (2) or extraordinarily long looking during the baseline trials - more than 2 standard deviations above the mean baseline looking time (1). The infants' names were retrieved from the birth records in the Greater Boston area and their parents were contacted by letter and by phone. Parents were compensated with token gifts (T-shirts, bibs and plastic cups).

Materials and Apparatus

The stimuli were roughly the shape of a flattened cone. They measured 15 cm in diameter at the base and 4.5 cm high at the center. The surfaces of these objects were completely coated in glued on sand[1]. A piece of string was attached to the top center of the object, allowing it to be raised and lowered without being held directly.

This experiment took place on a stage whose opening measured 38 cm x 88 cm x 34 cm and which was raised 100 cm from the ground level. There was a black felt backdrop for the stage which hid the movements of the experimenter. Attached to the front of the stage was a black screen which could be raised by the experimenter to partially obscure the display. The stage area itself was surrounded by black curtains from floor to ceiling. These curtains hid an observer who recorded looking time data and a video camera which recorded the subject. During the experiment, the lab was darkened and the stage was lit directly from above. The subject was lit indirectly for videotaping by lamps in front of and on either side of the stage.

The infant sat facing the stage with its head about 150 cm away and its eyes slightly above the floor level of the stage. The infant's parent/guardian sat on the infant's left facing away from the stage. Parents were instructed to interact with the baby as little as possible and to resist any urge to turn and look at the display. An observer could see the infant through an invisible hole in the black curtains. The observer could not see the stage however, and thus was blind to the details of the experimental manipulation. A white noise generator masked any sound from the movements of the observer and the experimenter. Looking time data were collected when the observer pressed a button connected to an IBM-486 computer every time the infants looked at the display. Trials ended when the infant looked away for 2 continuous seconds having looked for at least 0.5 s at the stage before that.

In general, for the experiments in this paper, there was one live observer. Each infant was also videotaped for off-line observation. Each live observer was highly trained and experienced. An observer is considered trained when his/her measurements correspond to those of another trained observer 95% in three consecutive sessions. The videotaped record of the infant was used to verify the measurements of the live observer. Coders of the videotapes were blind to the experimental conditions in which the infant was participating. The relationship between the looking time data as measured by the live observer and the looking time data as measured by the videotape observer was calculated as the inter-observer reliability and is reported for each experiment in the Results sections.

Procedure

Each subject was assigned to one of two conditions: the object-first condition (n=32; $\underline{M}_{age}$ = 8 months, 2 days) or the screen-first condition (n=32, $\underline{M}_{age}$ = 8 months, 7 days). The object-first condition was modeled on Wynn (1992) with two differences. First, objects were lowered from above rather than introduced from the side. This made the prediction of the location of the objects behind the screen straightforward. Second, infants were not habituated to the object placement.

Each condition consisted of three sections: an introductory section, baseline trials, and test trials. The introductory section served to acquaint participants with the novel object stimuli. The baseline trials served to introduce participants to the stage on which the objects were placed and to aspects of the events which were seen during the test trials -- namely, the lowering of objects, the raising and lowering of the screen, and the fact that objects lowered into a hidden location are later found in that location. These trials also provided a measure of any baseline preference the babies might have between arrays containing two objects and arrays containing one single object. Test trials immediately followed the baseline trials. During the test trials the babies were shown two objects hidden behind a screen one at a time. Looking times when the screen was removed revealed whether infants expected two objects on the stage.

Condition (screen-first, object-first) and object removed on one object trials (first-seen, second-seen) were between participants variables, whereas trial-type (baseline, test) and outcome (one object, two objects) varied within participants.

Object-First Condition

Introductory section. Every infant was given a 60 s exposure to the object before the experiment began. The experimenter held the object by its string and drew the infant's attention to the object. The experimenter then handed the object to the infant, who was allowed to play with it. If the infant was initially reluctant to grasp the object, the experimenter asked the parent to encourage the baby to handle the object.

Baseline trials. There were two pairs of baseline trials. The first pair took place entirely within the infant's view. The second pair was partially hidden by a screen. When looking time was not being monitored, that is, when objects were being introduced, the experimenter spoke to the infant, e.g., "Look (infant's name)! Watch the object!") to keep his/her attention to the stage area. The first pair of baseline trials consisted of a single object trial and a double object trial. In the single object trials the experimenter held an object by its string and introduced it into the display. The object was slowly lowered towards the stage floor and then stopped when it was about halfway down. It was then jiggled on its string for about 5 s and then lowered onto the stage floor. When the object reached the stage floor it was tapped five times and then released. The hand which held the object was retracted from the display and the experimenter signaled the observer to record the infant's looking at the stage area. In the double object trials, the subject saw two objects held by their strings lowered simultaneously towards the stage floor. The objects were stopped halfway down and then jiggled for 5 s before simultaneously continuing towards the stage floor. When the objects reached the stage floor they were simultaneously tapped five times and then released. The hands were then retracted and the baby's looking time was measured. After the baby looked away from the display the experimenter removed the stimuli by means of a movable flap in the bottom of the backdrop.

The second pair of baseline trials was partially hidden behind a screen. As in the first pair of trials, there were two types of trials: a single object trial and a double object trial. The single object trial began with the stage empty. The experimenter first raised the screen to hide the stage floor; then an object was lowered into the area above the screen until its lower part was hidden behind the top of the screen but its top was partially visible. The object was jiggled in that position for about 5 s and then it was lowered behind the screen onto the stage floor where it was tapped five times and released. The experimenter's hand was retracted and the screen was lowered to reveal the object sitting directly beneath where it was lowered. The experimenter then signaled the observer to begin measuring looking time. The double object trial began with the empty stage which was then hidden by the screen. Two objects were introduced into the area above the screen and simultaneously lowered behind the top of the screen so that they were partially hidden. There the objects were jiggled together for about 5 s and then lowered completely behind the screen. Upon reaching the stage floor they were tapped five times and then released. The screen was then lowered to reveal two objects sitting on the stage floor, and the infant's looking time at the objects in the display was measured.

There were four baseline trials - one of each type. The pair of trials without a screen always preceded the trials with a screen. Baseline trials alternated between one and two object outcomes in two orders (1-2-2-1 or 2-1-1-2). Order and side of the single object trials were counterbalanced across participants.

Test trials. Six test trials immediately followed the baseline/familiarization trials. During the test trials, the experimenter took care to draw the infant's attention to the objects as they were lowered by speaking to the baby until the second object had been released. First, participants were shown the empty stage. Next, a single object was lowered into one end of the display; it stopped halfway down, was jiggled for 5 s and then lowered, tapped five times on the stage floor and released. The hand that held the object was retracted and then the screen was raised to hide the object on the stage floor. Next a second object was lowered into the other end of the display behind the screen. This object was also stopped so that it was partially visible just above the top of the screen. It was then jiggled for 5 s and then lowered to the stage floor, tapped five times and released. After the second object was released, the screen was then lowered to reveal either one object (unexpected outcome) or two (expected outcome). The experimenter then signaled the observer to begin measuring the infant's looking at the display.

In the unexpected (single object) outcomes for half the infants, the object which was revealed after the screen was lowered was the object which had been seen to be lowered onto the stage in full view and for the other half the object which had been lowered, second, behind the screen. That is, for half of the babies, the object which disappeared had been seen sitting on the stage floor and for the other half, the object which disappeared was last seen going behind the screen. In addition, order of test outcomes (one object first, two objects first) and side of the single object (left, right) outcome were also counterbalanced across participants.

Screen-First Condition

Introductory section and baseline trials. The introductory exposure and the baseline trials were exactly the same in the screen-first condition as they were in the object-first condition.

Test trials. Six test trials immediately followed the baseline/ familiarization trials. Participants were first shown the empty stage and then the screen was raised before any objects were introduced. After the screen was in place the subject saw a single object lowered by its string towards the stage floor behind one end of the screen. The lowering was interrupted when the object was halfway to the stage floor and partially visible above the top of the screen. At this point the object was jiggled for about 5 s and then lowered completely behind the screen. The object was tapped five times on the stage floor and then released. The hand which held the object was then retracted from the display. A second object was introduced above the other end of the screen. It was lowered until it was partially hidden and then jiggled for 5 s before being lowered completely behind the screen. The second object was then tapped on the stage floor five times and then released. After the hand which lowered the object was retracted, the screen was removed to reveal either one object (unexpected outcome) or two (expected outcome). The experimenter then signaled the observer to begin measuring looking time.

As in the object-first condition, there were two different unexpected (single object) outcomes. For half of the infants, the single object which was revealed after the screen was removed was the object which had been first lowered and for the other half it was the object which had been lowered second. Moreover, the order of test outcomes (one object first, two objects first) and side of single object outcome (left, right) was counterbalanced across participants. Figure 1 schematizes the test trials in the two conditions with the single-object outcome (unexpected) due to the removal of the second object lowered.

Insert Figure 1 about here

Results

Overall, 59 of the 64 infants were videotaped[2]. The videotapes were coded by off-line observers who were completely blind to the experimental conditions. The on-line-off-line inter scorer reliability was 93%. In order to ensure that off-line observers were indeed blind to the experimental trials, we had an experienced observer guess the outcomes (1,2,1,2,1,2 vs. 2,1,2,1,2,1) in the test trials by viewing 15 randomly selected infants. He guessed the order of outcomes correctly in 8 of the 15 cases, which is no different from chance performance.

Preliminary analyses examined the effects of condition (object-first, screen-first), trial type (baseline, test), sex (male, female), outcome (one object, two objects) and order of outcome (one object first, two objects first) on looking times. There were no effects of sex or order of outcome. All subsequent analyses collapsed over these variables.

A four-way ANOVA examined the effects of condition (object-first, screen-first), and object removed (first object lowered, second object lowered) as between subject variables and trial type (baseline, test) and outcome (one object, two objects) as within-subject variables.

There was no main effect of trial type, that is, there was not a significant difference in overall looking time between baseline and test trials ($\underline{M}_{baseline} = 4.7$ s ; $\underline{M}_{test} = 5.0$ s). There was not a main effect of outcome; overall, infants preferred neither outcomes of one object nor outcomes of two objects. There was no main effect of which object was removed nor any interactions involving this variable. There was, however, a main effect of condition: $\underline{F}(1, 60) = 7.81$, $\underline{p} < .01$. Infants looked longer (collapsing over baseline and test trials) in the screen-first condition than in the object-first condition ($\underline{M}_{screen\text{-}first} = 5.4$ s; $\underline{M}_{object\text{-}first} = 4.3$ s).

Most importantly, there was a marginally significant three-way interaction between trial type (baseline, test), condition (object-first, screen-first) and outcome (one object, two objects): $\underline{F}(1, 60) = 3.889$, $\underline{p} < .05$. Figure 2 shows the mean looking times in the baseline and in the test trials of both conditions. To elucidate this 3-way interaction, more focused ANOVAs (reported below) examine the conditions separately.

Insert Figure 2 about here

Object-First Condition

A 2 x 2 ANOVA examined the effects of trial type (baseline, test) and outcome (one object, two objects) in the object-first condition. There was no main effect of trial type or outcome. However, the interaction between the two factors was significant: $F(1, 31) = 11.485$, $p < .005$. This interaction is due to the fact that the infants showed preference for the display of two objects in the baseline trials but looked longer at the unexpected outcome of one object in the test trials.

A 2 x 3 ANOVA examined the effects of outcome (one object, two objects) and trial number (first, second, third) on the looking times in the test trials alone and revealed a main effect of outcome: $F(1, 31) = 15.172$, $p < .0001$. Infants looked reliably longer at the unexpected outcome of one object than at the expected outcome of two objects. This pattern of preference was sustained over all three pairs of test trials: Trial 1: $M_{\text{one object}} = 4.9$ s, $M_{\text{two objects}} = 3.9$ s; Trial 2: $M_{\text{one object}} = 5.5$ s, $M_{\text{two objects}} = 3.4$ s; Trial 3: $M_{\text{one object}} = 4.0$ s, $M_{\text{two objects}} = 2.7$ s.

Recall that in the overall ANOVA, there was no main effect of which object was removed to create the impossible (one object) outcomes, nor any interaction involving this variable. The only effect one would expect of this variable, however, is on the impossible outcome test trials of the object-first condition (for it is only in this condition that the infant sees one object resting on the stage before the screen is raised to cover it, and then sees an outcome that either contains this very object or another one). We assessed the possibility that the object removed might affect looking times on the test trials in this condition with an ANOVA with two factors: object removed (first object lowered, second object lowered) and outcome (one object, two objects). The main effect of outcome described above emerged, of course: $F(1, 30) = 13.749$, $p < .001$. Infants looked reliably longer at the impossible outcome of one object. However, there was no main effect of which object was removed, and no interaction between these variables.

In sum, infants in the object-first condition differentiated the baseline trials from the test trials, looking longer at the impossible outcomes of one object only in the test trials. This pattern of results was confirmed by non-parametric analyses which revealed that 25 out of 32 infants showed a stronger preference to the unexpected outcome of one-object in the test trials than in the baseline trials (Wilcoxon Z = -2.97, $p < .005$, one-tailed).

Screen-First Condition

A 2 x 2 ANOVA examined the effects of trial type (baseline, test) and outcome (one object, two objects) on looking times in the screen-first condition. There were no main effects of either variable, and unlike the object-first condition, the interaction between the two factors was not significant: F(1, 31) = .059, ns (see Figure 4). To double check that infants did not differentiate the expected and the unexpected outcomes in the test trials alone, a one-way ANOVA examined the effect of outcome (one object, two objects) on looking times in the test trials. There was no effect: F(1, 31) = 1.344, ns.

In sum, 8-month-olds failed to determine whether there should be one or two objects behind a single screen in the test trials of the screen-first condition. This failure was confirmed by non-parametric analyses. Only 18 of the 32 infants in the screen-first condition showed a bigger preference to the unexpected outcome of one object in the test trials than in the baseline trials (Wilcoxon Z = -.23, ns, one-tailed).

An Important Group Difference?

Recall that there was a main effect of condition. Infants in the screen-first condition looked overall longer than did those of the object-first condition. This pattern holds as well for the baseline trials as for the test trials (see Figure 2). Since the baseline trials were identical across the two conditions, this pattern may reflect a random sampling difference between the two groups. Alternatively, the infants in the screen-first condition could have been "slower encoders" overall than those in the object-first condition. It is possible that this factor (encoding rate differences between the two groups) accounts for the failure in the screen-first condition, rather than the screen-first manipulation itself. Perhaps the slower encoders simply needed more exposure to the events in order to build a stable expectancy of two objects in the outcome, and they would have failed equally if they had happened to be placed in the object-first condition.

In order to check this hypothesis, we divided individuals in each condition into two groups on the basis of baseline looking times -- fast encoders and slow encoders. If encoding rate affects success, then fast encoders in each group should differentiate the test trials from the baseline trials better than slow encoders. Table 1 shows the baseline looking times for the fast encoders and the slow encoders in each group. Notice that the two groups overlap: the slow encoders in the object-first condition had longer looking times in the baseline trials than did the fast encoders in the screen-first condition. A four-way ANOVA examined the effects of trial type (baseline, test), condition (object-first, screen-first), outcome (one object, two objects) and encoding rate (slow, fast). There were no effects of encoding rate other than the main effect (slow encoders had longer looking times than fast encoders, obviously, since that is how the groups were constituted): $\underline{F}$ (1, 60) = 28.463, $\underline{p} < .001$. The faster encoders in the screen-first condition were not more likely to succeed than the slower encoders, nor were the slower encoders in the object-first condition more likely to fail (see Table 1).

We conclude, therefore, that the pattern of success in the object-first condition and failure in the screen-first condition (Figure 2) is due to the manipulation of interest -- the timing of the introduction of the screen.

Discussion

As predicted by the object file proposal, infants in the object-first condition performed better than those in the screen-first condition. The infants' success in the object-first condition extended the finding of Wynn (1992) and demonstrated that success in an object-first 1+1 = 2 or 1 task is quite robust. It is obtained with babies as young as 5 months (Wynn, 1992; Simon et al., 1995) under conditions of full habituation (Wynn, 1992) and under conditions of little familiarization (Experiment 1, this paper; Simon et al., 1995; Koechlin et al., under review). In Experiment 1, quite different objects were used than in the previous studies, and objects were introduced from the top instead of the side. This robust pattern of success indicates that young infants certainly distinguish arrays with one and two objects in them, and are capable of representing the outcome of the insertion of an object into a display already containing a hidden one.

The important new result of Experiment 1 was 8-month-olds' failure in the screen-first condition. If babies were simply counting the objects (as on the numeron list proposal) or incrementing an accumulator as each object is introduced (accumulator mechanism), it is difficult to see how the introduction of the screen would make such a dramatic difference. The object file proposal, however, predicts this result, on the assumption that a model of an object actually seen on the stage is more robust than a model constructed from memory, and thus can better accommodate a subsequent update. The difference in success between the object-first and the screen-first conditions of Experiment 1 is consistent with the difference in success between Baillargeon et al.'s (1995) $2 + 1 = 3$ or 2 condition and their $1+1+1 = 3$ or 2 condition.

The second prediction of the object file proposal tested in Experiment 1 was not confirmed. Infants did not perform better when the unexpected outcome was created by removing the first lowered object, even in the condition in which this object had actually been seen on the stage before the screen was raised (object-first test trials). This result suggests that babies are not representing the exact location of the objects behind the screen, rather encoding them simply as "one object behind the screen, another object behind the screen". Consistent with this proposal is Koechlin et al.'s (under review) finding that 5-month-old infants succeeded equally well at addition ($1+1 = 2$ or 1) and subtraction ($2-1 = 1$ or 2) when the outcomes were stationary and in predictable locations and when the outcomes were in unpredictable locations on a rotating plate behind the screen.

If one source of the infants' problems in constructing a model with two updates is individuating the locations behind the screen, then 8-month-olds might succeed in a screen-first (two update) 1+1 = 2 or 1 experiment if two separate screens were used. Experiment 2 explores this possibility. The baby is shown an empty stage, and two separate screens are placed on it. An object is lowered behind screen A, and the baby must update her model, creating a representation of an object behind screen A. Then a second object is lowered behind screen B, and the baby must operate on this model, updating it a second time to create a model of two hidden objects, one behind screen A and one behind screen B. The two separate screens, providing external markers for separate locations, may aid infants in updating their models twice.

The goal of Experiment 2 is to provide further insight into the nature of the models infants are constructing of the events in these addition experiments, to help pinpoint the source of the failure in the screen-first condition of Experiment 1.

Experiment 2

Method

Participants

Sixteen full-term 8-month-old infants (9 girls, 7 boys), ranging in age from 7 months and 15 days to 8 months and 14 days ($\underline{M}_{age}$ = 8 months, 0 day). Eight additional infants were excluded because of fussiness (7) and extraordinarily long baseline looking times (2 standard deviations above the mean) (1). Participants were contacted and compensated as in Experiment 1.

Materials

The materials were the same as in Experiment 1, except that the single screen was replaced by two, brightly colored screens, each measuring 35 cm x 35 cm. These screens were lavender and clearly contrasted with the blue stage and the black background of the rest of the stage display. When placed on the stage, the two screens were separated by a distance of 16 cm. The screens were introduced and withdrawn by the experimenter through an opening in the ceiling of the stage.

Procedure

The procedure was identical to that of the screen-first condition in Experiment 1. There was an introductory section, which served to familiarize the baby with the experimental stimuli. Next there were two pairs of baseline trials in which participants were familiarized with the apparatus including the two screens, and during which baseline preferences were measured. The baseline trials served to alert the infants to the fact that one object or two objects would be involved in these events, and that objects lowered on the stage would be seen where expected. Of course, they provided no information about what to expect in the crucial 1+1 = 2 or 1 test trials.

Unlike the participants in Experiment 1, participants in Experiment 2 were introduced to the screens after the introductory section and before the baseline trials. The subject was first shown an empty stage, then the two screens were lowered into place, side by side on the stage floor. The experimenter drew the infant's attention by calling out to the baby as the screens were lowered. Once the screens were on the stage floor the experimenter tapped her hand on the stage floor, first to the left of the two screens, then in the space separating the screens, and finally she tapped the other end of the stage to the right of the screens. The partially hidden trajectory of the hand served as an additional source of information that there were two separate screens on the stage. After this event, the screens were removed and the baseline trials were begun.

Introductory section. As in Experiment 1 each subject was given a chance to manipulate the object.

Baseline trials. There were two pairs of baseline trials. The events of the first pair happened in full view while the events of the second pair were partially hidden behind the two screens. Each pair consisted of a single object trial and a double object trial. In the double object trials, the objects were lowered simultaneously. Each lowering event followed the time course of the events of Experiment 1; objects lowered to the level of the top of the screens, jiggled for about 5 s, lowered and tapped on the stage floor. In the par of trials involving the screens, the screens were lowered simultaneously. For all familiarization/baseline trials involving screens, after the object(s) were lowered behind the screens, both screens were removed simultaneously before looking time to the display was measured. There were two orders of baseline trials (1-2-2-1 and 2-1-1-2). Order and side of the single object trials were counterbalanced across participants.

Test trials. Six test trials immediately followed the baseline trials. Participants saw an empty stage and then both screens were lowered onto the stage simultaneously. After the two screens were in place, the experimenter lowered one object towards one of the screens. At the same time she drew the infant's attention to the object by calling out to the baby, while jiggling the object for about 5 s partially behind the top of the screen, before lowering it and tapping it on the stage floor. When the object was partially behind the top of the screen it was stopped and jiggled for about 5 s and then completely lowered behind the screen, tapped on the stage floor and released. The experimenter's hand was then retracted from the display. The second object was then lowered behind the remaining screen the same way as the first. After the second object was in place and the experimenter's hand was retracted, both screens were simultaneously removed to reveal either one object (unexpected outcome) or two (expected outcome). Looking times at the outcomes were measured by hidden observers. Each infant saw an alternating series of test trials in one of two orders (expected first, unexpected first). The object which remained in the unexpected outcome was always that object which had been placed first on the stage (as in Wynn, 1992). Order of test outcomes and side of the single object (unexpected) outcome were counterbalanced across infants.

Results

As in Experiment 1, infants' looking times were measured by one live experienced observer and one videotape observer. The interscorer reliability for the infant looking times was 93%. As in Experiment 1, the videotape observers were blind to the details of the experimental manipulation and could not guess the order of outcomes.

Preliminary analyses examined the effects of sex and order of outcome on looking times. There were no effects of these factors. All subsequent analyses are collapsed across these variables.

A 2 x 2 ANOVA was conducted to determine the effects of outcome (one object, two objects) and trial type (baseline, test) on looking time. There were no main effects of trial type or outcome, but there was a significant interaction between these variables: $F(1,15) = 10.35$, $p < .01$. This interaction was due to the fact that, compared with the baseline trials, infants looked longer at the unexpected outcome of a single object during the test trials (see Figure 3).

Insert Figure 3 about here

A 2 x 3 ANOVA examined the effects of outcome (one object, two objects) and trial number (first, second, third) in the test trials alone. A main effect of outcome was revealed: $\underline{F}(1,15) = 9.222$, $p < .01$. Participants looked longer at the unexpected outcome of one object than the expected outcome of two objects. Moreover, this preference was sustained over all three pairs of test trials: Trial 1: $\underline{M}_{\text{one object}} = 4.8$ s, $\underline{M}_{\text{two objects}} = 4.6$ s; Trial 2: $\underline{M}_{\text{one object}} = 7.9$ s, $\underline{M}_{\text{two objects}} = 4.9$ s; Trial 3: $\underline{M}_{\text{one object}} = 5.0$ s, $\underline{M}_{\text{two objects}} = 2.8$ s.

This pattern of data is confirmed by non-parametric tests. Thirteen out of the 16 infants showed greater looking times to the one-object outcome in the test trials than in the baseline trials: Wilcoxon $\underline{Z} = -2.64$, $p = .01$.

Discussion

Infants succeeded in Experiment 2. The screen-first paradigm requires two successive updates of the infants' initial mental model of the empty stage, just as does the screen-first paradigm of Experiment 1. Thus, the number of updates of a model constructed from perceptual evidence cannot be the sole variable explaining the difference in success between the object-first and the screen-first conditions of Experiment 1.

It is likely that infants succeeded in Experiment 2 because the two screens provided continuously perceptually available markers of location, which helped the infants individuate the two objects in their model of the array. That is, they could encode one object behind screen A and the other behind screen B. The 5 1/2-month-old infants in Spelke, Kestenbaum, Simons & Wein's (1995) experiment and the 10-month-olds in Xu and Carey's (1996) experiment also set up models of two objects, each behind a separate screen, although in that case their evidence for two numerically distinct objects was that objects emerged from the outer sides of the two screens, in succession, without ever appearing in the middle. Thus, young infants can use visible markers of location to construct a mental model of objects hidden relative to those markers (behind them), even under conditions when they must create their models of the two objects in succession (two updates).

The fact that infants succeeded in the two-screen, screen-first condition of Experiment 2 suggests that one source of failure in the one-screen, screen-first condition of Experiment 1 was that the model of the array that infants constructed was "object behind the screen, another object behind the screen". With such an imprecise specification of location, the infants had some difficulty constructing or maintaining a representation of two numerically distinct objects behind the screen. Notice that the object-first condition of Experiment 1 required them to do this also, as do the experiments in Wynn (1992), Simon et al. (1995), Koechlin et al. (under review) -- their model must contain two numerically distinct objects behind the single screen. Apparently, it is the conjunction of the number of updates required in the screen-first condition and the lack of perceptually available markers of separate locations that accounts for the failure in the screen-first condition of Experiment 1.

Together, Experiments 1 and 2 provide support for the object file proposal. Subtle manipulations that would be expected to affect the robustness of the infants' mental models of the objects in the array determine success in 1+1 = 2 or 1 addition experiments with 8-month-olds. Similarly, the number of updates of a mental model affects success in 2+1 = 3 or 2 addition experiments with 10-month-olds (Baillargeon et al., 1995). The order of placement of the screens and objects (Experiment 1), or the number of screens (Experiment 2), or the grouping of the objects (Baillargeon et al., 1995) would not be expected to make any difference to the process of incrementing an accumulator (or stepping through a mental list of numerons) as each new object is introduced into the array.

Experiment 3 addresses the question of at what age infants would succeed on the screen-first condition of Experiment 1. Baillargeon et al. (1995) found that 10-month-old infants succeeded at a screen-first version of a 1+1 = 2 or 3 task. Notwithstanding this positive finding, there is a worry associated with this result. The unexpected outcome to their 1+1 task was three objects in an array. Longer looking at the unexpected outcome of three objects can mean either 1) that babies computed 1+1 = 2, or 2) simply that the array of three objects was more to look at than the array of two objects. However, this alternative explanation for success in Baillargeon et al.'s study is unlikely as they found no baseline preference for outcomes of 2 or 3. Experiment 3 seeks to confirm that 10-month-old infants succeed in a screen-first 1+1 task even when the unexpected outcome is less numerous than the expected outcome, that is, 1+1 = 2 or 1.

Experiment 3

Method

Participants

Sixteen full-term 10-month-old infants (7 girls, 9 boys), ranging in age from 9 months and 14 days to 10 months and 17 days ($\underline{M}_{\text{age}}$ = 10 months, 1 day) were tested. Six additional infants were excluded because of fussiness (4) and extraordinarily long looking during the baseline trials (2). Participants were contacted and compensated as in Experiment 1.

Materials

The materials were exactly as in Experiment 1. This experiment involved a single screen.

Procedure

The procedure was exactly as the screen-first condition in Experiment 1. The object which was displayed in the single object outcome trials was always that object which had been lowered first behind the screen as in Wynn (1992).

Results

Seven out of the 16 infants were observed by both a live observer and a second off-line observer from the videotaped record of the experimental session. Inter-observer reliability scores averaged 95%.

Preliminary analyses found no effects of sex and order of outcome on looking times. All subsequent analyses collapsed over these variables.

A 2 x 2 ANOVA examined the effects of trial type (baseline, test) and outcome (one-object, two-object) as within-subject variables. There were no main effects of trial type or outcome. There was, however, a significant trial type x outcome interaction: $F(1,15) = 5.977$, $\underline{p} < .03$ (see Figure 4). Infants preferred the single object outcome in the test trials but not in the baseline trials.

Insert Figure 4 about here

A 2 x 3 ANOVA examined the effects of outcome (one object, two objects) and trial number (first, second, third) on looking times on the test trials alone. There were no main effects or interactions involving these variables. However, a trial by trial analysis showed a consistent longer looking at the unexpected outcome of one object in all three pairs of test trials: Trial 1: $\underline{M}_{\text{one object}} = 7.1$ s, $\underline{M}_{\text{two objects}} = 5.5$ s; Trial 2: $\underline{M}_{\text{one object}} = 5.4$ s, $\underline{M}_{\text{two}}$

$_{\text{objects}}$ = 4.6 s; Trial 3: $\underline{M}_{\text{one object}}$ = 4.6 s, $\underline{M}_{\text{two objects}}$ = 3.5 s, compared to a baseline preference for two objects ($\underline{M}$ = 6.5 s) over one object ($\underline{M}$ = 4.8 s).

Non-parametric analyses confirmed that infants differentiated the baseline and the test trials. For 13 of the 16 infants, the preference for the unexpected single object outcome was greater in the test trials than in the baseline trials (Wilcoxon $\underline{Z}$ = -2.33, $p < .05$).

Discussion

These data confirm those of Baillargeon et al.'s (1995) in demonstrating that 10-month-old infants expected two objects as the outcome of the 1+1 addition performed in a single screen, screen-first experiment. It is clear that the capacity to construct models of multiple unseen objects is acquired gradually. During the period between 8- and 10-months, the infant overcomes the problems posed by a screen-first 1+1 task, but a screen-first 1+1+1 task exceeds the capacity of 10-month-olds (Baillargeon et al., 1995).

General Discussion

The success of infants much younger than 8-months of age in 1+1 = 2 or 1 addition tasks is well documented (Wynn, 1992; Simon et al., 1995; Koechlin et al., under review). Thus, the failure in the screen-first condition of Experiment 1 is striking. Such details of experimental procedure as the timing of the placement of the screen (Experiment 1), the number of screens (Experiment 2), and the grouping of the objects (Baillargeon et al., 1995) affect success in infant addition experiments. These results suggest that at least three factors may influence the robustness of the mental model the infant constructs of the objects in the array: 1) a model based on perceptual experience is more robust than one created in imagery; 2) each update of a mental model decreases its robustness; 3) perceptually available markers of distinct locations increase the robustness of models of distinct hidden objects.

A fourth factor plausibly influences robustness of infants' mental representations of the objects in an array: the complexity of the final model the infant must hold in memory. That is, models of one object are likely to be more robust than those with two objects, which in turn are likely to be more robust than those with three objects, even though infants can, as can adults, hold three individuated entities in mind at once. The idea that it is the complexity of the final model constructed, the output of all the updates, that determines robustness, allows us to explain a striking and puzzling regularity in the infant/toddler arithmetic data: infants succeed on subtraction tasks more robustly than on addition tasks. In Wynn's (1992) original study, 5-month-olds differentiated the outcomes in the 1+1 = 2 or 1 version more weakly than in the 2-1 = 1 or 2 version, as did the infants in the study of Koechlin et al. (under review). This result could be due to a preference for the more numerous outcome (the impossible outcome in the subtraction version is 2 objects, in the addition version, 1 object), but there was no baseline preference for 2 objects in these studies. Further, Wynn (in press) reports a parallel result in a paradigm that removes a comparison between two outcomes of different numerosities as a factor in these studies. The outcomes were kept constant and the events to be updated were varied. In one condition, half the subjects saw 2+1 = 3 and half saw 3-1 = 3. In the other condition, half the subjects saw 2+1 = 2 and half saw 3-1 = 2. Infants' looking time was overall greater when the outcomes did not match the addition/subtraction events, but this result was entirely due to the condition in which the outcome was 3 objects (where the impossible outcome was the result of subtraction). Finally, in Starkey's (1992) addition and subtraction studies, subtraction was systematically easier.

It is difficult to see how the symbolic counting models would account for subtraction being easier than addition. In subtraction, the counter must be incremented to the maximum value of the set before an object is removed, and then adjusted downward.

During addition, the counter is simply incremented to the maximum value of the final set. However, the object file model discussed herein predicts that subtraction will be easier than addition for pairs that differ in the number of items in the final model (e.g., 1+1 vs. 2-1; 2+1 vs. 3-1). Models of "2" constructed in imagery are less robust than models of "1"; models of "3" constructed in imagery are less robust than models of "2". Also, it is plausible that operations on models created from perceptual experience which involve deletions of objects in the model are easier, and thus yield more robust representations, than those which involve additions of objects to the model.

The object file model, as we have sketched it here, embodies a construction which entails the notion of "robustness of the model". The idea is that the factors that decrease the quality of a model lead, with varying probabilities, to the baby's inability to maintain a short term memory representation of what is on the stage, just as a variety of factors interfere with an adult's short term memory representation of a set of visual figures, e.g., confusability of items, modality specific interference, etc. (Allport, 1989). Recently, Munakata, McClelland, Johnson & Siegler (1994) have appealed to and modeled strength (or robustness) of a representation of a hidden object as a possible account of greater estimates of infants' knowledge from looking times than from reaching measures.

The effects of order of screen placement, number of screens, grouping of objects and addition versus subtraction are consistent with the object file account of infant performance in the addition and subtraction experiments, and they are not consistent with the accumulator or numeron list models. On the latter models, the infant increments a counter for each new object introduced into the array, arriving at a symbolic representation of their number. Then when the screen is removed, the infant engages in another count, comparing the results. In such a scenario, there is either no reason for the manipulations studied in these experiments to matter, or, in the case of the addition/subtraction comparison, for the manipulations to favor subtraction.

A proponent of the symbolic models might counter that these studies do not decisively rule against the accumulator model or the numeron list model; after all, a mental model of the objects in the array may be the input to a counting device. We agree that this is a logical possibility and reply: 1) It is certainly not the case that a mental model of the objects in the array is necessary as input to a counting device. Imagine an experiment in which 15 beans are placed, one by one, behind a screen, the screen removed, revealing either 15 beans of 14 or 16. Adults would not solve this task by constructing a mental model of 15 distinct objects behind a screen; this number exceeds our capacity for parallel individuation (Trick & Pylyshyn, 1994). Yet, we could detect the impossible outcomes by counting and comparing counts. 2) Our aim has not been to show that human infants do not have an accumulator representation of number, or a numeron list representation. Rather, we argue that there is as of yet no good evidence for such symbolic representations of number in human infants. Instead, current results are best accounted for by an object file model.

One other consideration strongly favors the object file account of the infant number experiments, and that is the limit of 3 or 4 items in both the habituation studies and the addition studies. The accumulator has no such limit -- pigeons have been trained to count larger numerosities (Rilling & McDiarmid, 1965), nor is there any theoretically motivated reason to suspect that an innate numeron list would have such a limit. However, such a limit is predicted by the object file account, for we know there is a limit on parallel individuation, the number of distinct objects that can be simultaneously tracked in a visual model of an array (Trick & Pylyshyn, 1994).

There is one result in the literature in support of infants' symbolic representation of number, and that is that infants can enumerate entities other than objects (e.g., sounds: Starkey, Spelke & Gelman, 1990; syllables, Mehler & Christophe, 1995; jumps of a doll, Wynn, 1995). True, but the object file model is not that objects are the only entities infants can individuate and build imagistic models of. Indeed, we would expect that any entities infants can individuate are also entities they can model. However, Starkey et al.'s (1990) demonstration that infants are sensitive to cross modal correspondences between 2 drum beats and 2 visually presented objects, or 3 drum beats and 3 visually presented objects, suggests that infants do have an abstract, symbolic representation of number, at least, of small numbers. We agree that this is the best single piece of evidence for the symbolic account of infant numerical competence, but counter that it is possible that the infants are capable of detecting one-one correspondences between individuated entities in models in different modalities (a possibility that Starkey et al., 1990, themselves, suggested as one account of their data). Also, unlike the well established findings from visual habituation studies, and from infant addition/subtraction studies, the empirical robustness of the cross-modality matching results is in question (cf. Mix, Huttenlocher & Levine, under review; Mix, Levine & Huttenlocher, 1994).

In sum, we suggest that the weight of evidence currently available supports the proposal that the representation of number underlying infants' successes and failures in the addition experiments consists of mental models of the objects in the arrays. These representations are numerical in that they require that the infant have criteria for numerical identity (the ability to distinguish one entity seen on different occasions from two numerically distinct entities), because a representation that instantiates $(\exists x)(\exists y)((\text{object}(x) \ \& \ \text{object}(y)) \ \& \ x \neq y \ \& \ \forall z(\text{object}(z) \rightarrow (z=x) \lor (z=y)))$ is logically equivalent to "There are two entities", and because comparisons among models are on the basis of one-one correspondence among individuals. However, they fall short of symbolic representations of number, as there is no unique symbol for each integer, because there is no counting process defined over them.

The developmental changes in infants' model building capacities between ages 5 and 10 months may have several sources. General information processing capacities may increase (e.g., see Diamond, 1991, for a review). Alternatively, infants' knowledge of objects, per se, may become more elaborated, allowing them to take into account more information about objects and their locations in constructing mental models of the arrays. Xu and Carey (1996) document a major change of this sort between ages 10 and 12 months, when infants begin to use evidence other than spatiotemporal information in object individuation. Most probably, both types of changes contribute to the developmental progression witnessed in these studies.

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Footnotes

1 The objects were originally part of a series of experiments designed to compare infants' knowledge of properties of solid objects and non-solid substances. For that study, objects were made to look similar to a portion of sand. In the present study infants were given much evidence that the stimuli were objects: subjects handled the stimuli and saw the objects moved, lifted and shaken. Thus, that they looked like a pile of sand is irrelevant to the present study.

2 Videotapes of 5 infants were lost due to equipment failure.

Figure Captions

Figure 1. Schematic drawings of the test trials in Experiment 1 (object-first and screen-first conditions).

Figure 2. Mean looking times for Experiment 1.

Figure 3. Mean looking times for Experiment 2.

Figure 4. Mean looking times for Experiment 3.

Table 1. Mean looking times in Experiment 1 as a function of rate of encoding

	Baseline Trials		Test Trials	
	One object	Two objects	One object	Two objects
<u>Object-first</u>				
Fast encoders	2.6 s.	3.6 s.	4.1 s.	3.3 s.
Slow encoders	5.8 s.	6.2 s.	5.4 s.	3.4 s.
<u>Screen-first</u>				
Fast encoders	3.6 s.	3.7 s.	5.6 s.	5.1 s.
Slow encoders	7.6 s.	6.8 s.	5.8 s.	5.1 s.

Object-First Procedure

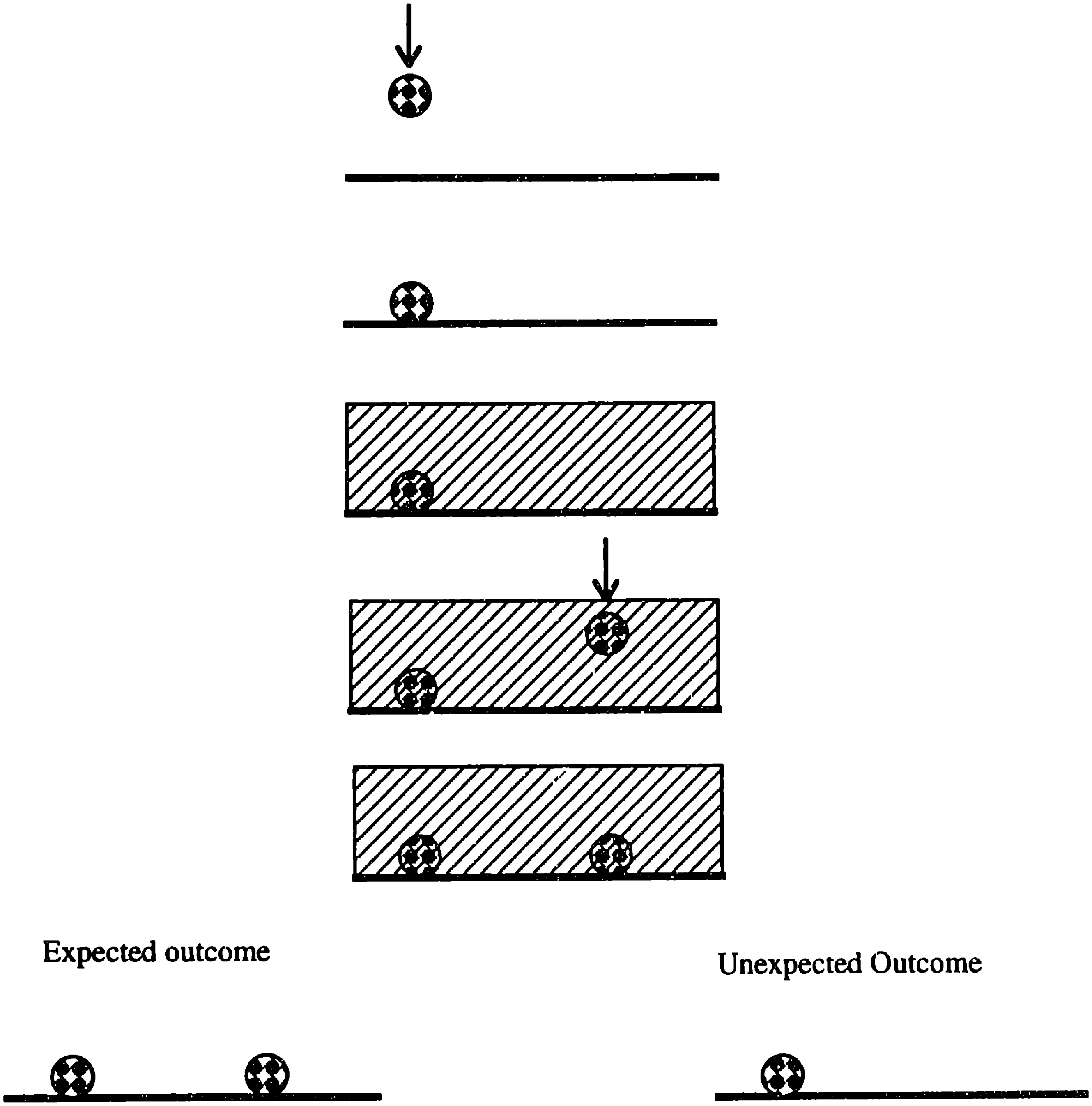


Figure 1

Screen-First Procedure

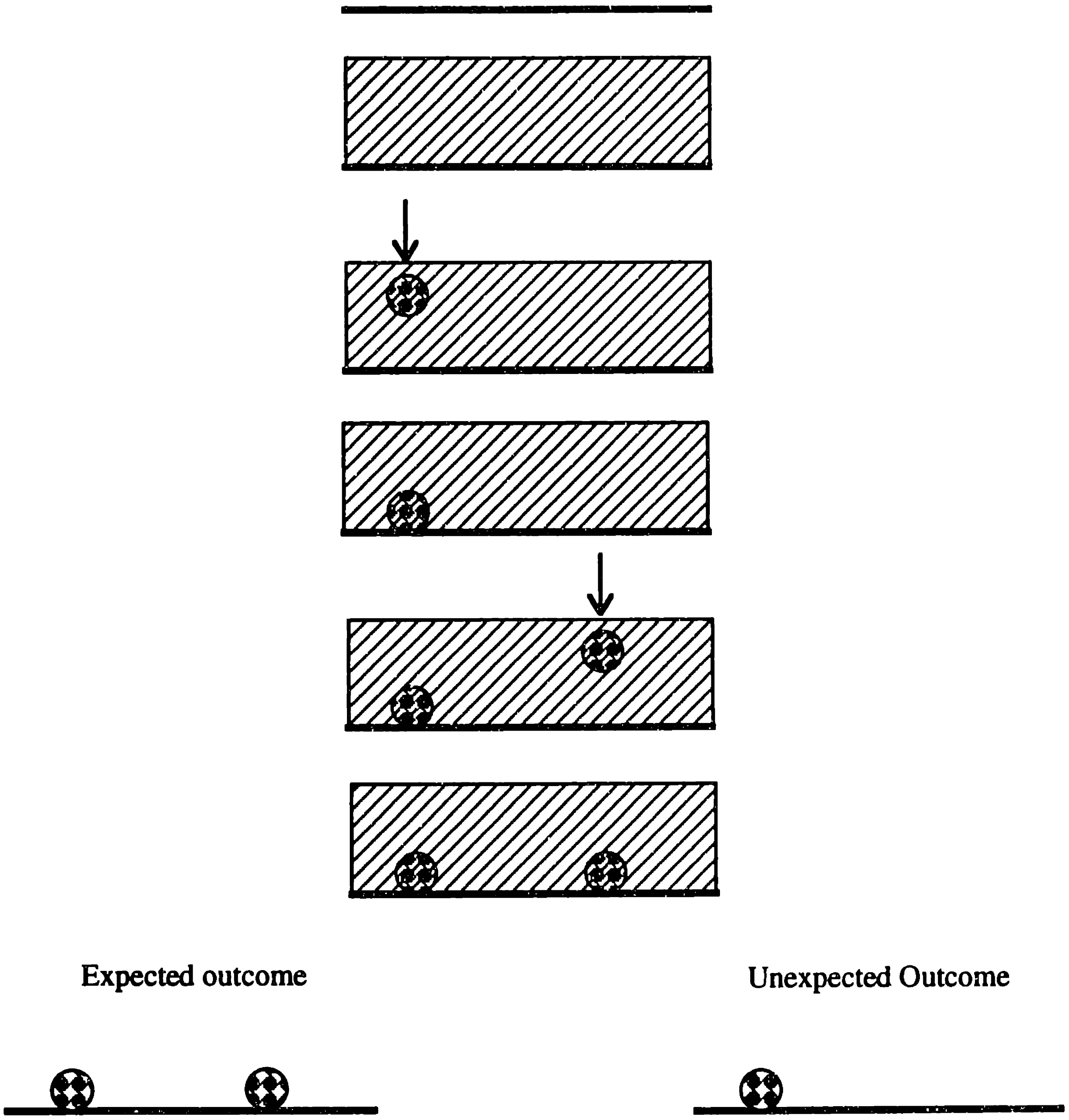
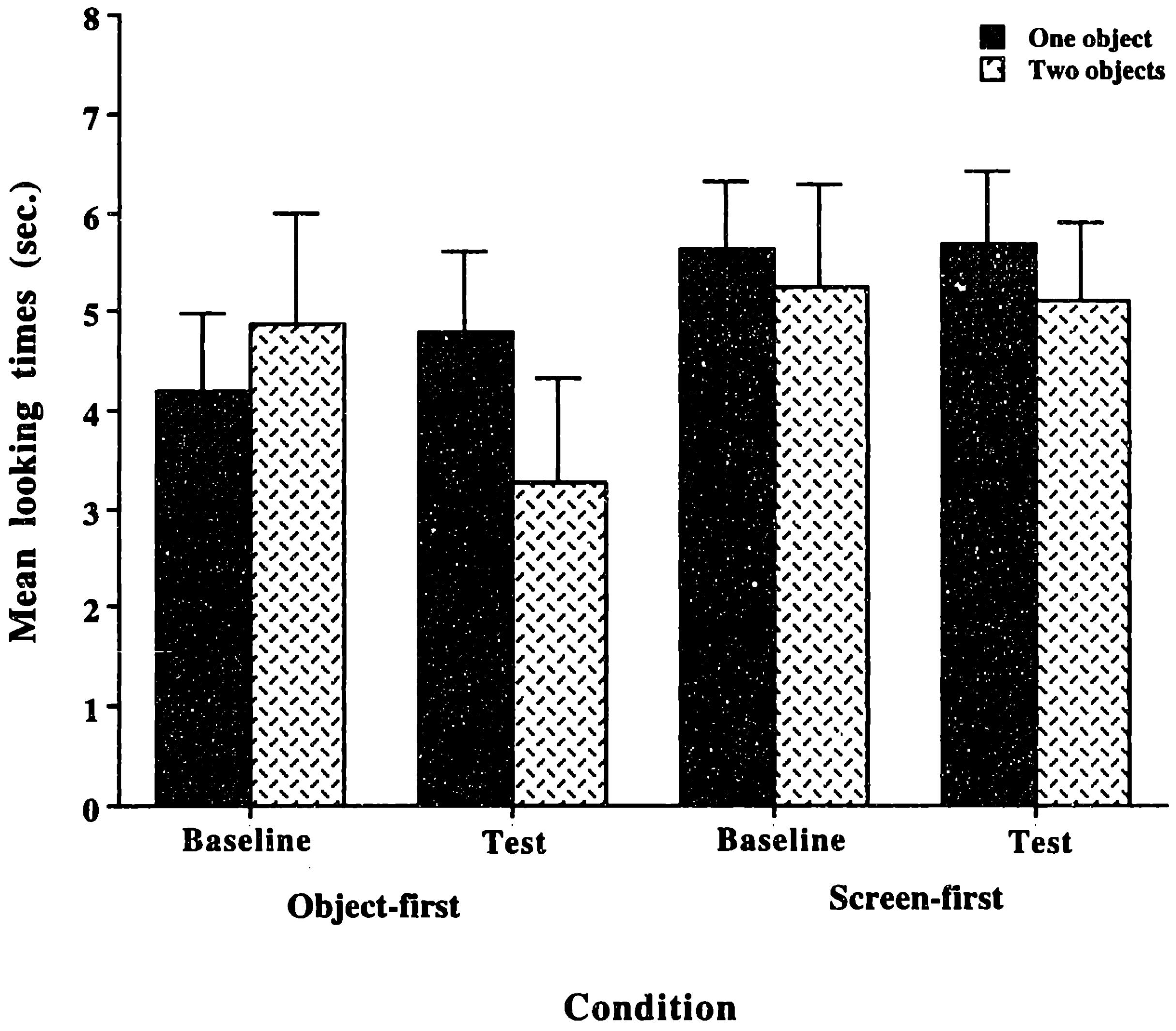


Figure 1



8
7
6
5
4
3
2
1
0
Mean looking times (sec.)
One object
Two objects
Baseline
Test
Baseline
Test
Object-first
Screen-first
Condition

Figure 2

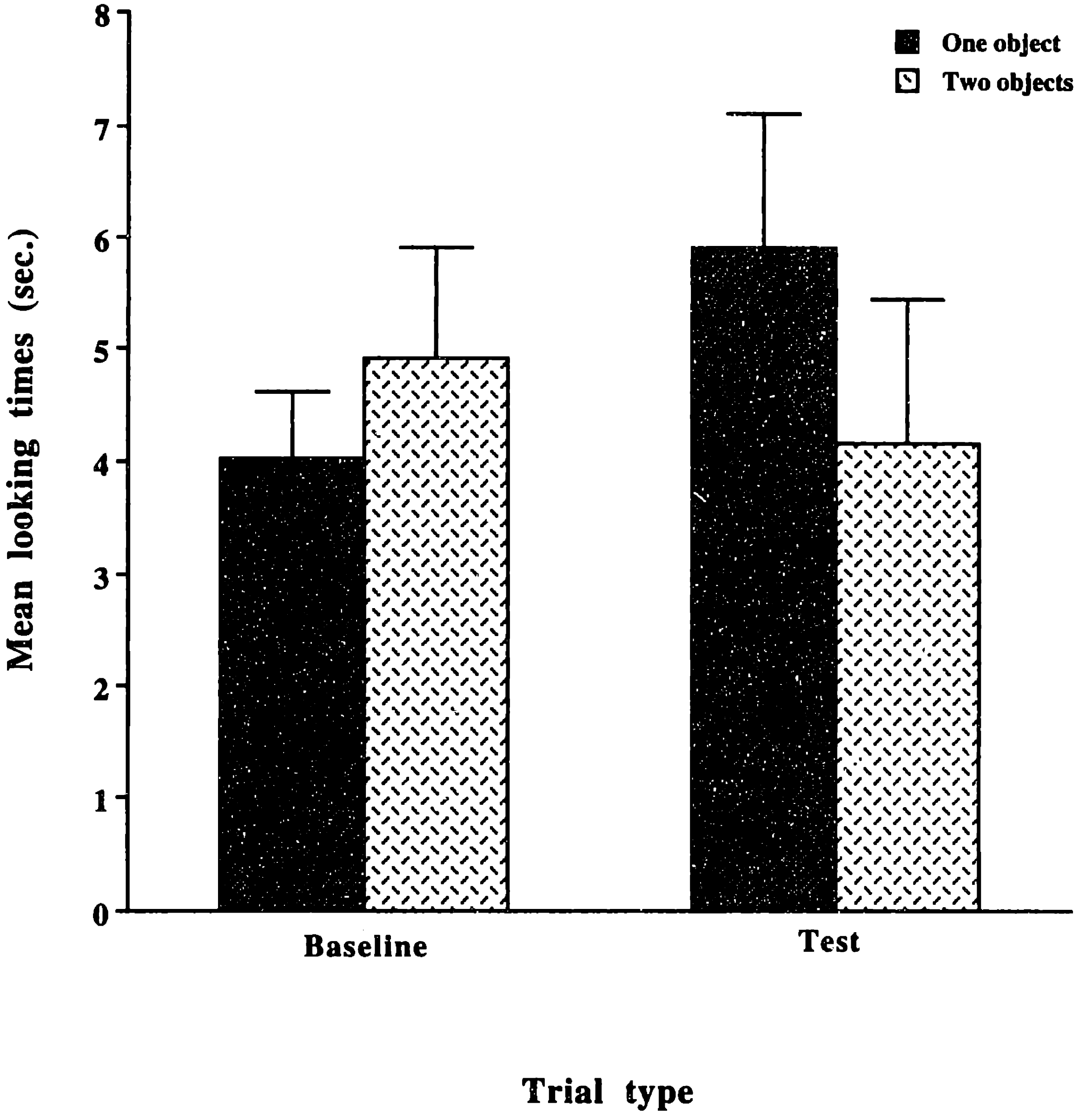

Mean looking times (sec.)
0
1
2
3
4
5
6
7
8
■ One object
▨ Two objects
Baseline
Test
Trial type

Figure 3

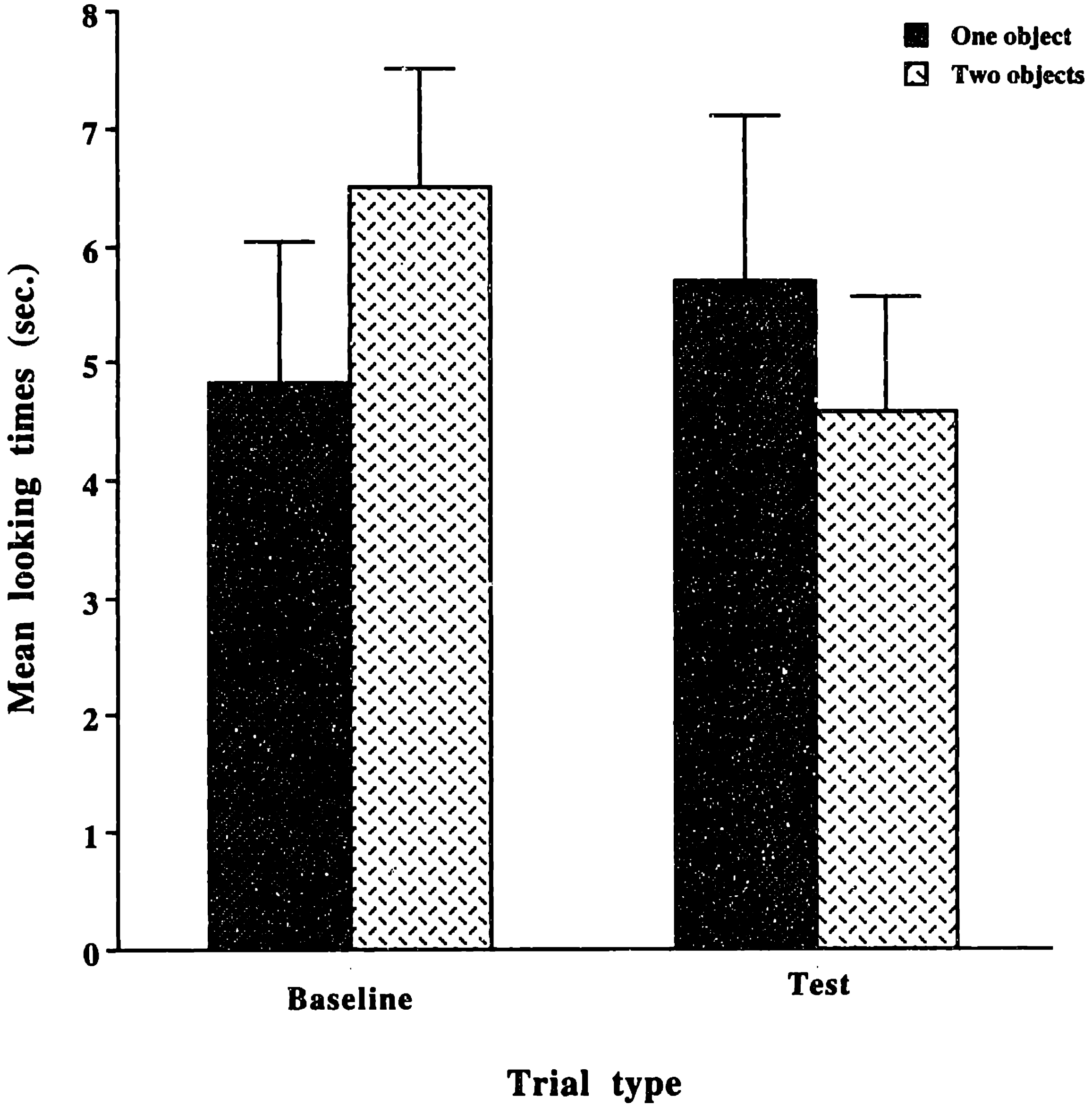

8
7
6
5
4
3
2
1
0
Mean looking times (sec.)
One object
Two objects
Baseline
Test
Trial type

Figure 4

Chapter III

Evolutionary roots of the human numerical capacity:
Experiments with two nonhuman primate species

Introduction

Recent work in the field of cognitive development has advocated the view that human cognitive architecture is characterized by domain-specific modules. The general idea is that knowledge of the world is divided into different content areas or cognitive domains (Baillargeon, 1995; Carey, 1995; Carey & Spelke, 1994; Leslie, 1994; Spelke, Breinlinger, Macomber & Jacobson, 1992). These domains are organized according to different theoretical frameworks, which constitute lay understanding of different areas of knowledge, e. g., language, number, intuitive mechanics, and so forth.

Under the psychological viewpoint, researchers have explored the mental processes involved in number comprehension and production both in humans and in nonhuman animals in search for the characterization of abilities which are uniquely human versus abilities which can be found across species. Investigations show that the domain of number embodies a variety of processes that have been explored in different experimental paradigms in the animal field (see Davis & Pérusse, 1988 and Gallistel, 1990, for extensive reviews of numerical capacities in animals) and in the human field, both in adult cognition and cognitive development (Gallistel & Gelman, 1992; Gelman & Gallistel, 1978; Dehaene, 1992; Wynn, 1990, 1992). These studies suggest that different types of numerical representations seem to be present in various different species.

Specifically with respect to humans, number embodies a particular department of knowledge because of the relationship it establishes with the uniquely human language faculty. There are different ways that human adults can express number. Although perhaps unlikely, it is possible for humans to use their fingers to represent number in tallies or to use their eyes and blink numbers in temporally distinct intervals. The most natural way, however, for humans to express number is through the linguistic system. Number is most directly expressed in language when individuals are counted -- "one, two three, ..." There seems to exist an important relationship between the concept of number and its linguistic expression.

One prominent position that addresses this relationship is sponsored by Chomsky (1980, 1988). On Chomsky's view, the number faculty depends upon the language faculty. An essential aspect of human numerical system is the property of discrete infinity. That is, humans can generate an infinite quantity of numbers on the basis of adding one to the first fundamental numerosity one ad infinitum. Chomsky proposes that this property can only emerge from a generative system such as the one that underlies human language. The generativity of language can be characterized as the infinite use of finite means -- that is, language provides a finite number of elements and rules for combining them (Chomsky, 1980). This allows humans to generate an infinite combination of sentences. The human numerical system is thus characterized by this same type of generativity. This system provides rules for productively yielding integers and for creating an infinite quantity of arbitrary numbers. According to Chomsky, this isomorphism between number and language is due to the fact that the human numerical system comes as a by-product of the human linguistic capacity (Chomsky, 1988).

The human numerical capacity embodies a special case of the numeron-list system (Gelman & Gallistel, 1978; Gallistel & Gelman, 1992). The numeron system for counting is a symbolic system where mental representatives (symbols, numerons) are mapped onto the numerosities counted. For example, adult humans seemingly have numerons such as "!" and "@" that stand for numerosities such as one and two. The human numeron-list system is a special case of numeron system given that it is generative. It exploits the generativity of language because it allows for the creation of another and another number ad infinitum. It allows humans to write and understand any arbitrary number. It provides an algorithm for producing any integer for arbitrary numerosities.

There is reason to doubt, however, that young human children have this generative numeron system. For example, human children, before age 6, do not have the concept of discrete infinity, that is, they do not understand that there is no highest number -- the concept of discrete infinity (Evans & Gelman, 1981). Moreover, children do not work out the mapping between their initial understanding of number and the linguistic numerical system until age 3 1/2 (Wynn, 1990). That is, children before this age do not realize that there are linguistic labels -- number words -- which correspond to specific numerosities and that these tags correspond to numerosities of sets or arrays of objects. Before age 3 1/2, children reproduce the counting list of number words without understanding that there is a meaning for each of the items in the list (Wynn, 1990). Thus, despite the fact that children have quite developed linguistic knowledge by age 3 1/2, they do not present, until that age, a full numeron system of counting. Although it is possible that language allows for children to arrive at this stage, this achievement does not seem to be part of the language faculty.

Is there anything specific about human representations that allows humans to create a numeron system for representing number? One way to look into this question is by analyzing the animal literature on counting. It is not entirely clear whether animals have a numeron-list type of numerical representation. Several studies have shown that rats and pigeons can learn to discriminate number of responses of numerosities up to 24 (rats) and 50 (pigeons) in tasks utilizing the operant technique (Capaldi & Miller, 1988; Rilling & McDiarmid, 1965). Monkeys have also been shown to easily learn to discriminate paired numbers of stimuli (Douglas & Whitty, 1941; Hicks, 1956; Thomas & Chase, 1980) and tell the ordinal relationships among them (Washburn & Rumbaugh, 1991). Lastly, various species of animals have been studied as single cases and have been shown to discriminate numerosities (a dolphin: Mitchell, Yao, Sherman & O'Regan, 1985; a raccoon: Davis,

1984) and count (a parrot: Pepperberg, 1987). All these studies suggest that different types of numerical representations seem to be present in various different species. However, none of these experiments show that the numerical capacities of these animals embody a numeron-type representation of number.

The number literature on chimpanzees, on the other hand, gets closer to a characterization of learned capacities that may be more comparable to those of humans. That is, chimpanzees can be taught to count and to assign symbolic tags for numerosities from one to nine (Boysen, 1993; Boysen & Berntson, 1989; Matsuzawa, 1985; Matsuzawa, Itakura, & Tomonaga, 1991). Sheba (Boysen, 1993), for example, has reached a stage where she seemingly has a limited numeron system. Her numerical system may be characterized as a limited numeron system because she knows symbols that correspond to each different numerosity. Much the same way children learn that /wun/ corresponds to one, Sheba has learned that "1" corresponds to one, "2" to two, etc. In the numeron system, the attribution of linguistic labels or any symbolic tags to the numerons is assigned arbitrarily. The fact that we write "1" or say /wun/ for a corresponding mental symbol '!' that stands for the real numerosity one is arbitrary. We could as well call one, 'thrap', as we could call two, 'sket', and so forth and so on. In addition, Sheba also understands the ordinal relationships between such numerosities. In this respect, the numerical knowledge of this chimpanzee is largely comparable to that of a 3 year old human child.

What differs, however, is that the chimpanzee is not likely to ever spontaneously generalize what number comes next in the counting list. There is no evidence that the chimpanzee reaches an understanding that there can be more numbers generated after the number just learned. There is no evidence that the chimpanzee will learn the list of numbers that 3 1/2 year old human children learn so quickly once they realize how the system works. Therefore, there is no evidence that the system of this particular animal or the stage she reached is generative and can produce an infinite number of symbols.

Another difference between the chimpanzee's and the human child's developing numerical capacities is that it is extremely hard for Sheba to learn this numerical system. Sheba learned the mapping between numerical symbol and numerosity over a period of two years (Boysen, 1993). It was required that she undergo multiple sessions of numerous trials per day. Along the process, the number of sessions could vary from 4 to 12, in which the number of trials could vary from 20 to 975. Thus, it seems that the chimpanzee's capacity for number depends on the long and hard process of training. Moreover, in the end, the chimpanzee's system does not achieve the property of generativity. One possible reason for this difference may be that the human linguistic representational system provides the means for a symbolic representation of number to be expressed. Is there anything specific about the structure of the human language that makes it easier for human children to learn the symbolic numeron system?

Number is fundamental in the grammar of languages. Numerical concepts are picked out by quantifiers such as “one”, “a” and “another”. Number can be marked in nouns and verbs, usually denoting the distinction singular/plural. Concepts such as one and two are part of the human language faculty because they underlie the concepts of "one" and "another". The concept of one is obligatorily marked in the syntax of languages. Every time we use count nouns, a numerical concept is implicitly expressed. If these concepts are automatically grammaticized in language, therefore, by virtue of the fact that humans present language, it may be that they are spontaneously available. It is possible that an automatic representation of number in language (i.e., one is the fundamental notion of our numerical system; from one you can generate the whole infinite number system) might allow human beings to spontaneously represent number and ultimately construct a symbolic numeron-type of representation.

In order to consider the possibility that language provides the means for humans to acquire the symbolic numeron system one should investigate nonlinguistic creatures. One way to look into this question is by examining the evidence from the human infant research on number. Human infants as young as neonates can spontaneously discriminate numerosities of 2 and 3, and sometimes 4 (e.g., Antell & Keating, 1983; Starkey & Cooper, 1980; Strauss & Curtis, 1981; van Loosbroek & Smitsman, 1990). They can match small numerosities and tell small numbers of objects, events, and sounds (Starkey, Spelke & Gelman, 1990). They can add and subtract objects hidden behind screens in small numerical events (Wynn, 1992; Chapter II; see Chapter II also for a discussion on possible models to account for these results). Therefore, it is possible that the language faculty plays a role in providing the environment for the later development of the symbolic numeron system. At least, evidence from the infant studies suggest that human infants have spontaneously available rudimentary numerical representations.

An alternative is to examine the evidence from the nonhuman primate research on number. As covered before, monkeys and apes can be taught quantity discriminations, numerosity discriminations, number tag assignments and addition (see Chapter I for a review of this literature). However, the most important characteristic of this research is the amount of training these animals are subjected to. Contrary to the human infant research that suggests that rudimentary numerical representations are spontaneously available, the nonhuman primate research explores questions regarding the capacity monkeys and chimpanzees are able to acquire when submitted to extensive training. It is possible that these animals have spontaneous representations that are not being selectively tapped by this methodology. Alternatively, it is possible that these animals are elaborating specific representations which do not necessarily need to be numerical on the basis of task requirements. It may be the case that there are task-specific demands that require the animals to develop particular strategies to solve such tasks.

Thus, on the one hand, investigation with prelinguistic infants show a spontaneous rudimentary numerical capacity. On the other hand, investigation with nonhuman primates show that, <u>under extensive training</u>, the animals can be taught to discriminate numerosities, assign numerical symbols and add. In order to establish whether nonlinguistic primates and prelinguistic human infants present comparable spontaneous numerical capacities it is necessary to explore the use of the same experimental measure -- the preferential looking and violation of expectancy technique -- with both species. If spontaneous numerical representations are only available to humans, then it is possible that number is fundamentally tied to the human language faculty, being a by-product of the uniquely human linguistic capacity. Alternatively, if nonhuman primates are shown to present comparable spontaneous numerical capacities, just as the ones shown with human infants, then it may be that the number faculty is more fundamental than hypothesized, thus not being uniquely human.

The current studies

In our search for the spontaneously available representations of number, we tested two evolutionarily distantly related species to human beings, one Old World monkey species, rhesus macaques, and one New World species, cotton-top tamarins (*Saguinus oedipus oedipus*). This paper focuses on the capacity of such two nonhuman primate species to perform simple arithmetic operations. In the infant literature, many studies have indicated that human infants understand numerical relationships between one object and another object in 1 + 1 tasks (Chapter II here; Koechlin et al., under review; Simon et al., 1995; Wynn, 1992).

In the nonhuman primate research, Hauser, MacNeilage & Ware (1996) tested adult rhesus macaques (*Macaca mulatta*) using preferential looking/violation of expectancy tasks which were modified versions of Wynn's (1992) 1 + 1 = 2 or 1 and 2 - 1 = 1 or 2 tasks. The design was modified due to the availability of subjects offered by the opportunity to work with a huge population (app. 900 animals) of semi free-ranging rhesus macaques in Cayo, Santiago, Puerto Rico. Here we will focus on the addition task only.

Each monkey received two familiarization trials and one test trial. In the familiarization trials, the monkeys were presented with the outcomes of the test trials and the addition or subtraction operation they would see in the test trial. In the test trial, the monkey was presented with the 1+1 operation. The monkeys were divided into two groups, 1 + 1 = 2 and 1 + 1 = 1. In the 1 + 1 = 2 group, the monkeys saw 1 object being placed into a box; then a second object was placed into the box -- 1 + 1. After the operation was completed, the screen was removed and the monkeys saw the expected outcome of 2 objects. In the 1 + 1 = 1 group, the monkeys again saw 1 object being placed into a box; then a second object was placed into the box -- 1 + 1, except that, when the screen was removed, they saw an unexpected outcome of 1 object only. Thus, the comparison between expected and unexpected events was performed between subjects.

The results showed that the monkeys in the conditions with the unexpected outcome (1 object) looked longer in the test trial than in the familiarization trials, whereas the monkeys in the conditions with the expected outcome (2 objects) did not look longer in the test trials than in the familiarization trials -- that is, the results suggest that the rhesus monkeys may have expected to see two objects in the addition task. This result embodies a methodological innovation in the investigation of spontaneous representations of number in nonhuman primates. These results suggest that the numerical abilities available to human infants are shared with at least rhesus macaques. However, it is still an open question whether the monkeys is this study can compute the exact outcomes of the addition operation. That is, in two 1 + 1 = 2 or 1 studies, it was not shown whether the monkeys had an explicit understanding of the exact number of objects to be found in the array. In order to find out whether rhesus' numerical capacities parallel those of human babies, we conducted two further experiments with rhesus monkeys. Results are presented in Part I.

In Part II we present four 1 + 1 experiments conducted with cotton-top tamarins. In all the tasks, the number of objects involved in the outcomes of 1 + 1 addition operations was manipulated. The questions addressed in these experiments are the same as in the rhesus case, namely, whether this very distant species would be able to compute the exact number of objects in the arrays, thus revealing comparable capacities to human infants.

In adapting the infant preferential looking/violation of expectancy method for use with nonhuman primates, several changes in the experimental arrangement had to be made. First, new apparati were built for both populations. This was necessary 1) so that they could be carried along in the field studies and 2) in order to fit the size of the animals -- tamarins are rather small. Second, because pretesting had suggested that non-food items were inappropriate for testing the monkeys, the stimuli were clearly edible objects -- in the rhesus case, eggplants; and, in the tamarin case, objects made of cereal (well known to them). Third, we found that the size of the stimuli was also a relevant factor for interest (or lack thereof) in this technique. In a pilot study, the tamarins were tested in a 1 + 1 = 2 or 1 task with entire apples as the stimuli. The monkeys did not pay any attention to the apples, leading us to scale down the stimuli.

Changes were also made to the experimental design. In the infant addition studies (Wynn, 1992; Chapter II here), babies were presented with either habituation or familiarization trials before the test trials. In Wynn (1992), for example, babies were habituated to one and two objects until they reached a particular criterion before they proceeded on to three pairs of test trials. In the experiments presented in Chapter II, on the other hand, babies were familiarized to a baseline condition of one and two objects before the three pairs of test trials were presented.

As discussed before, the design used by Hauser et al. (1996) was different from that used with the infants in two respects. First, the number of trials was limited to fit the conditions of testing. That is, in the semi free-ranging population of rhesus in Cayo, environmental conditions could interfere with the attention span of the experimental subjects, such that they would not sit through 10 trials of an experimental session, as do human infants.

Second, since the potential subject pool in the island of Cayo was large, a between-subjects design was adopted in lieu of the usually adopted within-subjects design for infants. Hauser et al. (1996), at first, tested the rhesus monkeys in an adapted design in which each monkey only received one trial, either a familiarization or a test trial. In a second condition, another set of monkeys received two baseline trials and one test trial. For the rhesus experiments in the present paper, we maintained the same design as that described for the second condition in Hauser et al. (1996).

The tamarin experiments mirrored and were adapted from the experiments presented in Chapter II of this thesis. As in the rhesus case, the design was shortened to present each monkey with four baseline trials and two test trials. Two pairs of baseline trials were utilized to provide enough information about the outcomes of the test trials the monkeys would see and to familiarize them with the placement of the screen, in order to avoid the argument of success being due to a novelty effect -- interest in novel configurations during the test trials. However, contrary to the rhesus experiments, the design was maintained as a within-subjects design to accommodate the fixed number of subjects of the laboratory population.

I. Studies with Rhesus Macaques

a. Subjects and study environment

Experiments were conducted on a semi-free-ranging population of rhesus monkeys living on the island of Cayo Santiago, Puerto Rico (see Rawlins and Kessler, 1987 for a description of the island and the history of research on this population). The population consists of approximately 900 individuals, divided into five to six social groups. The island is inhabited only by rhesus monkeys. There are no predators on the island. Personnel of the Caribbean Primate Research Center provide food (Purina monkey chow) once in the morning, distributed across three feeding dispensers on the island. The monkeys' diet also includes natural food products from the island, including coconut, grass, leaves, and flowers. Subjects are extremely well habituated to the presence of human observers and individuals can be easily recognized from unique chest tattoos and ear notches. Maternal kinship, age and sex are available from a long term data base. In this population, females reach adulthood at approximately three years whereas males reach adulthood at approximately four years.

All rhesus monkeys run in the two experiments reported below were adults. For Experiment 1, a total of 14 subjects were tested in the 1 + 1 = 2 (expected) condition, whereas 16 subjects were tested in the 1 + 1 = 3 (unexpected) condition; 48 additional subjects were tested but failed to complete the sessions. For Experiment 2, a total of 7 subjects were tested in the 1 + 1 = 2 (expected) condition, whereas 10 subjects were tested in the 1 + 1 = big 1 (unexpected) condition; 29 additional subjects were tested, but failed to complete the entire session due to environmental distractions. Sessions were aborted if any of the following occurred: (1) subjects failed to look steadily at the entire presentation, (2) a distracting social interaction occurred during the period when looking time was being recorded, (3) the subject moved away as soon as the looking time period started, or (4) the time elapsed between successive trials within a session exceeded five minutes. Using these relatively stringent criteria, our success rate for a completed session (i.e., two familiarization trials and one test trial) was 38%.

b. Experiment 1: 1 + 1 = 2 versus 1 + 1 = 3

Hauser et al. (1996)[1] showed that rhesus monkeys succeeded in two versions of a 1 + 1 = 2 or 1 + 1 = 1 task, as well as in a 2 - 1 = 1 or 2 - 1 = 2 task. That is, in all of these studies, looking times at one and two objects were compared in a between subjects 1 + 1 = 1 versus 1 + 1 = 2 condition and in a 2 - 1 = 1 versus 2 - 1 = 2 condition. The monkeys looked longer at the unexpected outcome of 1 object in the addition task when compared to their looking times at 2 objects and at the unexpected outcome of 2 objects in the subtraction task when compared to their looking times at 1 object. These results may imply that the monkeys did set up expectations for the number of objects to be found behind the screen.

However, it is also possible that the monkeys had no understanding of what the precise outcome for the addition of 1 + 1 should be. Specifically, at least two alternative explanations can account for the results to date. First, it may be the case that the monkeys succeeded because they formed expectations to see numerical variance, namely, a numerical change from one object to something different in the outcome. That is, the monkeys may expect to see something different from one in the outcome of the 1 + 1 operation. Second, it might also be the case that the monkeys succeeded in 1 + 1 tasks because they expected to see more than one object behind the screen, but not necessarily exactly two.

Experiment 1 was conducted to address these hypotheses. The monkeys were presented with either an expected condition of 1 + 1 = 2 or an unexpected condition of 1 + 1 = 3. They were shown one object placed into a box behind a screen; then a second object was placed into the box, also behind the screen. The screen was removed to reveal either two objects (expected outcome) or three objects (unexpected outcome). If the monkeys set up expectations to see numerical variance or to see more than one object as the result of the 1 + 1 operation, then the outcomes of two and three objects are equally acceptable. If, on the other hand, the monkeys set up expectations for exactly two objects as the result of the 1 + 1 operation and not for a numerical change in what is behind the screen, or for more than one object, then they should succeed by looking longer when they see three objects rather than two in the box.

Experimental Design

Materials and Apparatus

The apparatus consisted of a box constructed out of foam core (40 cm x 25 cm x 25 cm). The top was open and the front panel consisted of a removable screen with a concealed cloth pouch on the back side (i.e., facing away from the monkey).

To maintain consistency with Hauser et al. (1996), we used purple eggplants as stimuli. Eggplants are generally unfamiliar to the monkeys since they are not provided as part of the provisioning nor have individuals had experience eating them. Nonetheless, monkeys appear to be sufficiently interested in looking at them, without approaching. Due to the experimental work conducted previously (Hauser et al., 1996), at least some of the subjects tested in the experiments reported here will have seen eggplants.

Design and Procedure

The experimental protocol used in this experiment was identical to that reported in Hauser et al. (1996), except for the specific number of objects used in the familiarization trials and test trials. Specifically, this experiment used a screen first design -- the screen is placed to hide the interior of the box before the objects are placed behind it. Familiarization and test trials of Experiments 1 and 2 are illustrated in Figure 1.

Insert Figure 1 about here

The experiment consisted of 3 trials, 2 familiarization and 1 test trials. Each session took between 5-10 minutes. Familiarizations were devised to provide the monkeys with some experience of both the outcome of the test trial and the event of the 1 + 1 addition operation. We expected, as in prior research, that such familiarizations would eliminate the added interest which might arise from seeing novel or unfamiliar events or outcomes.

The monkeys were divided into two groups, 1 + 1 = 2 and 1 + 1 = 3. The first group received two familiarization trials and a test trial involving 1+1 = 2. The second group received two familiarization trials and a test trial involving 1+1 = 3. The 1 + 1 = 2 group was presented two familiarizations (F1 and F2), half receiving F1 first and the other half receiving F2 first. In F1, the empty testing box was presented. Then, two eggplants were lowered one at a time, as in the addition 1 + 1 operation, into the empty open box. Looking times were recorded for 10 seconds, starting when the eggplants were in place. In F2, subjects saw the testing box with the screen in place. The screen was then removed, revealing two eggplants which had been previously placed into the box. Looking times were recorded for 10 seconds, starting when the screen was removed. The 1 + 1 = 3 group also received two familiarizations (F1 and F3), half receiving F1 first and half receiving F3 first. F3 started with the presentation of the testing box and the front screen in place. The screen was then removed, revealing three eggplants. Test trials for each group consisted of the same addition operation, 1 + 1, except that the number of eggplants revealed upon removal of the screen was different. Specifically, an open testing box was presented, the screen was placed and then, in succession, two eggplants were placed behind the screen. When the screen was removed, the 1 + 1 = 2 group saw two eggplants whereas the 1 + 1 = 3 group saw three eggplants. Looking times were recorded for 10 seconds as soon as the screen was removed.

Subjects were tested when they were resting and either alone or in relatively small social groups, 5 to 10 animals. When a subject was located, we set up the apparatus and the video camera and then proceeded to run the individual experimental sessions. One experimenter and two observers were involved in both experiments. While the experimenter presented the stimuli, one observer recorded the trial on video (Panasonic IQ404, Sony Hi-8) and a second observer looked out for possible events that might distract our subjects and read out loud the sequence of conditions to be run. The video camera, presentation box and test subject were lined up in a straight line so that the video record provided an unambiguous, head on view of the subject's eyes. In video taping a trial, we attempted to fill as much of the recorded image with the subject's head as possible.

Analog video records were digitized onto a Macintosh Quadra 950 using the Radius VideoVision board. Frame-by-frame quantification (30 frames/second) of the total amount of time looking at the display (out of 10 seconds) was then scored using the Adobe Premiere (version 4.2) software. A look was defined as visual fixation in the direction of the display for a minimum of 5 frames (approximately 0.17 seconds). One observer scored all of the experimental sessions. An additional observer scored 20 of these sessions. They were blind to the experimental conditions run. Inter-observer reliability was 92%. Data from the primary observer was used in the present analyses.

Results

An alpha-level of .05 was selected for the statistical analyses in all of the following experiments.

Figure 2 shows the mean looking times at two and three objects in the different familiarization and test trials. For both groups, individuals showed a significant decrease in looking time from the first familiarization to the second (Expected: $t(13) = 8.25$, $p = 0.008$; Unexpected: $t(15) = 8.12$, $p = 0.008$). For subjects in the 1+1=2 condition, there was a statistically non-significant decrease in looking time from the second familiarization to the test ($t(13) = 2.91$, $p = 0.10$); 11 out of 14 subjects showed this pattern of response. In contrast, subjects in the 1 + 1 = 3 condition showed a statistically significant increase in looking time from the second familiarization trial to the test trial ($t(15) = 9.81$, $p = 0.004$); 15 out of 16 subjects showed this pattern of response.

Insert Figure 2 about here

Thus, consistent with earlier findings (Hauser et al., 1996), monkeys appeared to expect two objects when they saw two objects disappear behind a screen. They looked longer when they saw three objects after having seen two objects being placed behind the screen. The looking times from familiarization to test trials increased only when the rhesus monkeys saw three objects but not two objects. The monkeys apparently expected to see two objects in the test trials regardless of the number of objects they had seen in the familiarization trials. The results of Experiment 1, thus, rule out the possibility that the monkeys succeeded in 1 + 1 tasks either because they expected to see an outcome that differed from one object when the screen was removed or because they expected to see an outcome of more than one object when the screen was removed.

c. Experiment 2: 1 + 1 = 2 versus 1 + 1 = big 1

The monkeys' success in 1 + 1 = 2 or 1 + 1 = 1 (Hauser et al., 1996) and 1 + 1 = 2 or 1 + 1 = 3 (Experiment 1 here) suggests that the monkeys expect to see two objects behind the screen upon its removal. However, an alternative explanation would be that the monkeys were encoding amount of stuff. For example, infants in 1 + 1 = 2 or 1 and 1 + 1 = 2 or 3 experiments (Wynn, 1992; Chapter I here; Simon, Hespos & Rochat, 1995; Baillargeon, Miller & Constantino, 1995) and in 1 + 1 = 2 versus 1 + 1 = 3 (Wynn, 1996); and rhesus monkeys in 1 + 1 = 2 versus 1 + 1 = 1 (Hauser et al.,1996) and in 1 + 1 = 2 versus 1 + 1 = 3 (Experiment 1 here) might have looked longer at the unexpected outcomes not because there were either more or less individual objects than were observed being placed behind the screen. Rather, subjects might have attended to the amount of stuff in the display -- doll stuff in the case of the human infants and purple eggplant stuff in the case of the rhesus monkeys. The current study addresses this possibility. In the present experiment, the monkeys were familiarized with a large eggplant, roughly twice the volume of one of the eggplants used in the 1 + 1 operation[2]. If the monkeys are only expecting consistency in the volume of purple stuff in the display then, following familiarizations, they should show either no change or a decline in looking time to both the two eggplant outcome and to the large eggplant outcome. In contrast, if subjects are individuating the actual objects in the arrays, then they should look longer if they see a single large eggplant (unexpected) than if they see two smaller eggplants (expected).

Experimental Design

Materials and Apparatus

The testing apparatus used in this experiment was exactly the same as described for Experiment 1. The stimuli were two small purple eggplants roughly the same size as the ones utilized in Experiment 1, and one additional large eggplant, roughly equivalent in size to the two smaller eggplants, dubbed as the "big 1" object.

Design and Procedure

The procedure, design and analytical tools underlying this experiment were identical to the ones in Experiment 1, with one exception. Here we present the monkeys with a 1 + 1 = 2 (expected) condition and a 1 + 1 = big 1 (unexpected) condition. Familiarization and test trials are illustrated in Figure 1.

Subjects in the 1 + 1 = 2 group received the same F1 and F2 familiarizations as described for Experiment 1. Subjects in the 1 + 1 = 2 or big 1 group received the F1 familiarization trial and a novel F4 familiarization trial. F4 involved presenting the testing box with the screen in place. The screen was then removed, to reveal the one large (big 1) object. The 1 + 1 = 2 group received the same test as in the previous experiment. The 1 + 1 = big 1 group saw an empty testing box, followed by the placement of the front screen. Subsequently, one eggplant and then a second one were lowered behind the screen. When the screen was removed, the big 1 object (large eggplant) was revealed.

The procedure for testing the subjects and for scoring videotapes was exactly the same as described for Experiment 1. The same coders who scored the looking times of the monkeys in the previous experiment scored all 17 of the present experimental sessions as well.

Results

For both the expected and unexpected conditions, subjects showed statistically significant decreases in looking time from the first to the second familiarization (Expected: t (6) = 1.64, p = 0.018; Unexpected: t (9) = 2.24, p = 0.037) . Figure 3 shows the mean looking times at two objects and one big object in the familiarization and test trials.

Insert Figure 3 about here

For the test trial in the expected condition (1 + 1 = 2), subjects again showed a statistically significant decrease in looking time (t (6) = 2.50, p = 0.029); 6 out of 7 subjects showed this pattern of result. In contrast, when subjects received the unexpected test, they showed a statistically significant increase in looking time (t (9) = 2.00, p = 0.049); 9 out of 10 subjects showed this pattern of response. Taken together, these results show that the monkeys individuated the actual objects in the arrays and looked longer when they saw a single large eggplant (unexpected) than when they saw two smaller eggplants (expected). Thus, they did not represent objects in arrays on the basis of consistency in the volume of purple stuff in the display.

Discussion

Taken together, the results of Experiments 1 and 2 of Part 1 extend the results of Hauser et al. (1996). In Experiment 1, we addressed the question of whether the rhesus monkeys, like human infants, have precise understanding of the results of the addition operation. Indeed, the monkeys looked longer when there were three eggplants rather than two in the box, showing that at least this species individuated the actual objects presented in the display, setting up expectations to see precisely two objects as the screen was removed.

In Experiment 2, we showed that it is unlikely that the rhesus monkeys' successes in addition tasks are due to monitoring amount of purple stuff since, when shown an outcome of a large eggplant two times as large as the two little eggplants added together, the monkeys tended to look longer at the outcome of one large eggplant than at the outcome of two small eggplants.

Rhesus monkeys' preferential looking patterns in these studies suggest that rudimentary number conceptual representations may constitute part of nonhuman primates' cognitive architecture. At the very least, these studies provide evidence that the spontaneous representations involving number of objects in arrays are present in at least one species of nonhuman primate more distant, evolutionarily, from humans than are apes.

In order to make these studies comparable to earlier results of Hauser et al. (1996), the same design was adopted in the present two experiments. However, there is a potential confound in this design. Recall that the 1 + 1 = 2 group of both Experiments 1 and 2 received two familiarizations in which they saw either two objects in the box upon removal of the screen or two objects added one at a time into the empty box without the screen. In the 1 + 1 = 3 group, as well as the 1 + 1 = big 1 group, however, the monkeys received one familiarization with the operation of 1 + 1 and a familiarization with three objects or one big object in the box upon removal of the screen. It is possible that the monkeys in the 1 + 1 = 2 group were familiarized to twoness faster and thus looking times decreased faster than the monkeys in the 1 + 1 = 3 or 1 + 1 = big 1 groups because of amount of exposure. This familiarity problem might have contributed for the longer looking times in the groups where familiarizations were one of each type -- two and three objects, in Experiment 1, and two and big 1 objects, in Experiment 2. In the next series of experiments this confound was resolved in that the design followed a within-subjects procedure in which all monkeys received the same familiarizations.

Until this point, rhesus macaques were the only species on which numerical tests using the preferential looking/violation of expectancy method were performed. To expand the generalization that spontaneous numerical representations are widely shared amongst phylogenetically related species, we conducted four experiments with an evolutionarily more distantly related species than rhesus macaques.

II. Studies with Cotton-top Tamarins

a. Subjects and study environment

The following experiments were conducted with a captive population of cotton-top tamarins. Cotton-top tamarins are originally from South America, where they inhabit the upper canopies of the tropical rain forest of northwestern Colombia. Tamarins in general are distributed from the northern part of South America -- Amazon forest, Peru, Bolivia, Colombia, Panama and Costa Rica, to the Atlantic forest areas southeast of Brazil.

Tamarins have a relatively small body size (average = 9 in), long legs, short arms and a long tail (average = 14 in.) (Rylands, 1993).

The ten subjects of the present studies were five adult females and five adult males. In the laboratory, animals reach adulthood at approximately 3 years of age. The subject age range is 3-8 years of age. The monkeys are housed in breeding pairs in cages at William James Hall, Harvard University. They were originally obtained from the New England Regional Primate Research Center, Southborough, MA where they were born. Although there is vocal and visual contact among the families, it is limited by vegetation placed amongst the cages. The individuals are kept at approximately 10% below their normal body weight in captivity, more comparable to what it would be in the wild. The monkeys are generally motivated to participate in the studies. During the experimental sessions, edible items are used as stimuli and provided as food. The amount of food is generally believed to be adequate to keep the monkeys attentive to the task. The monkeys have previously participated in operant tasks on abstract concept formation and on means-ends manual search tasks. None of the other experiments the monkeys had participated in used the preferential looking/violation of expectancy method or concerned number.

The same 10 animals participated in each of following four experiments. In order to avoid a decline in attention to the objects in the tasks, these experiments were interspersed by 4 to 6 weeks. In addition, the color and configuration of the Fruit loop composites used as stimuli varied for each experiment. The experiments were conducted in the Primate Cognitive Neuroscience Laboratory at William James Hall, Harvard University, in a small room that was familiar to the monkeys. Other experiments have also been carried out in the same testing room. The subjects were brought into the lab in a plexiglas box measuring 50 cm x 50 cm x 50 cm. During testing, the monkey was transferred to a plexiglas chamber which measured 70 cm x 70 cm x 100 cm with a partition inside in the shape of a pyramid where the subject sat or stood. The pyramidal interior of this chamber constrained the movements of the monkeys and also helped center the monkeys. With the exception of the lateral sides, which were opaque, all parts of the testing chamber were transparent. The lateral sides were opaque to reduce distraction by limiting the monkeys' visual surrounding and to help the subject focus attention on the experimental apparatus. When the subject was brought into the testing room, the testing apparatus, a video camera, the experimenter and an observer were already in place. The video camera was always set up to focus on the experimental monkey.

b. Experiment 3: $1 + 1 = 2$ versus 1

In Experiment 3, we presented the monkeys with a $1 + 1$ operation in which the outcome was either an expected result of 2 objects or an unexpected result of 1 object. The idea behind this experiment was to investigate whether cotton-top tamarins, a more distantly related species to human beings than rhesus monkeys, would succeed in a task comparable to the one conducted with rhesus monkeys. Success in this task would allow us to extend the capacities observed in human infants and rhesus macaques to a more evolutionarily distant non-human primate.

Experiment 3 employed a split-screen design -- that is, the apparatus contained two separate screens instead of a single one, behind which objects could be placed. We started with this design because we wanted the apparatus to be familiar to the tamarins. Given that the monkeys had never been tested in preferential looking/violation of expectancy tasks before, we feared they might not attend to the events if we used an unfamiliar setting. Previous studies on memory and manual search had used this apparatus and therefore the monkeys were already familiar with it. Moreover, a split-screen apparatus was shown to yield positive results with young infants (Chapter II here). Therefore, in order to maximize success, we favored the use of this apparatus.

Experiment 3, as well as all other experiments in Part II, utilized a within-subjects design given the constraints of the fixed number of animals in the lab population. This is a major difference from the studies with the rhesus monkeys conducted in Cayo, where the availability of subjects allowed for a between-subjects design. In the experiments reported in Part I, for example, each monkey received two baseline trials and one single test trial -- that is, each monkey either saw the expected outcome of two objects or the unexpected outcome of one object as the test trial. In the present experiment, each monkey received the same four familiarization trials and the same two test trials with counterbalances.

Experimental Design

Materials and Apparatus

The testing apparatus was a box made of plexiglas. It measured 30 cm x 30 cm x 30 cm. The front panel was made of clear plexiglas (top half) and opaque plexiglas (bottom half and frame). The rest of the box was made of opaque plexiglas. On the top part there were two small doors that concealed two slots through which the Fruit Loops were placed. The doors were also made of opaque plexiglas. They measured 4 cm x 4 cm. Familiarization and test trials of experiments in Part II are illustrated in Figure 4.

Insert Figure 4 about here

The apparatus was placed onto a stage-like table. There was a black backdrop around the apparatus that concealed the experimenter. This backdrop was placed 10 cm behind the stage where the apparatus was placed so that the experimenter could easily manipulate the objects out of view from the subjects. There was an opening cut on the backdrop the same size as the apparatus so that the experimenter put her hands through to manipulate the objects. The objects, as well as the hands of the experimenter, always appeared from behind this backdrop.

The stimuli were two identical objects each consisting of two green Fruit Loops[3] glued together one on top of the other perpendicularly. They measured 2 cm in diameter at the base and 2.5 cm high at the center. Figure 5 shows all the stimuli used in the experiments of Part II.

Insert Figure 5 about here

All of the following experiments were conducted in the same testing room as described above. The protocol for bringing in the monkeys into the lab, as well as the testing chamber used to house the test monkeys in the sessions were exactly the same as described above.

Design and Procedure

The experiment consisted of 3 phases. Phase I was a familiarization condition that served to acquaint the subject with the apparatus and the objects used as stimuli. Phase II was a baseline condition which served to introduce the subject to the placement of objects behind the screens, the opening and closing of the screens, and the fact that objects introduced into hidden locations are later found in the same locations. The baseline trials also served to obtain a measure of the subject's preference for one-object arrays or two-object arrays. Phase III consisted of two test trials, one with an expected outcome and one with an unexpected outcome. Each session (familiarization and test trials) took approximately 5 minutes to run. After each pair of trials, subjects were given 1/4 of a Fruit loop. This procedure was adopted in all of the following experiments and served the purpose of keeping the monkeys interested in watching the events. Giving the monkeys this quantity of Fruit loop was not associated with a particular action and thus, did not serve as reinforcer in any sense.

Familiarization phase. Each monkey was given a 30 s exposure to the apparatus and the objects before the experiment began. The experimenter's hands were drawn through the opening in the backdrop holding one object. She captured the monkey's attention by showing the object close to the front panel of the testing chamber. The experimenter always held the object until the monkey had looked at it for at least 2 s.

Baseline phase. There were two pairs of baseline trials. The first pair took place entirely within the monkey's view, that is, the screens which covered the slots were open at all times. When objects were being introduced, the experimenter drew the attention of the monkey by showing the object close to the front of the testing chamber, directly in front of the monkey's face. The first pair of baseline trials consisted of a single object trial and a double object trial. In the single object trials the experimenter held one object and introduced it into the testing apparatus, showing it to the monkey through the transparent top front panel of the box. The object was jiggled in front of the monkey for 5 s before being placed into the open slot. The hand which held the object was then retracted from the display and the experimenter made sure that the monkey saw that the hand was empty. The experimenter then signaled to the observer to start the 10 s count while recording the subject's looking time. In the double object trials, the monkey saw two objects held at the same time, one by each hand of the experimenter. The objects were jiggled in front of the monkey for 5 s before being placed simultaneously into the slots, one object in each slot. The hands were then retracted while the experimenter made sure that the monkey saw they were empty and the monkey's looking time was recorded. After 10 s elapsed, the experimenter removed the stimuli by grabbing them and putting them behind the box out of view of the monkey.

For the second pair of baseline trials, screens were placed in front of each slot, and the objects were hidden behind the separate screens. As in the first pair of trials, there were two types of trials: a single object trial and a double object trial. The single object trial began with open slots. The screens were then closed to hide the empty slots. Then an object was shown to the monkey through the transparent top front panel of the box. The object was jiggled in front of the monkey for 5 s before being placed behind one of the screens. The hand which held the object was retracted from the display and the experimenter made sure that the monkey saw that the hand was empty. The screens were opened to reveal one object sitting in the location where it had been placed. The experimenter then signaled to the observer to start the 10 s count while recording the subject's looking time onto the video camera. The double object trial also began with open slots. The screens were then closed to hide the slots. The monkey saw two objects held at the same time by the experimenter's two hands. The objects were jiggled in front of the monkey for 5 s before being placed behind the screens. The hands were then retracted while the experimenter made sure that the monkey saw they were empty. The screens were then opened to reveal two objects sitting behind them. The subject's looking time was recorded. After 10 s elapsed, the experimenter removed the stimuli by grabbing them and putting them behind the box out of view of the monkey.

The baseline trials alternated between one and two object outcomes in two orders (1-2-2-1 or 2-1-1-2). The pair of trials without a screen always preceded the trials with a screen. Order of outcome (one object first, two objects first) and side of one object trials (left, right) were counterbalanced across subjects.

Test phase. Two test trials immediately followed the baseline phase. As in the baseline phase, the experimenter took care to draw the monkey's attention to the objects as they were being lowered by presenting the objects close to the monkey's face. First, the monkey was shown the empty slots. The screens were then closed to hide the slots. One object was then presented to the monkey. The experimenter jiggled it for 5 s and then placed it into one of the slots behind the screen that covered it. The hand that held the object was retracted and the experimenter made sure that the monkey saw that it was empty. Next, a second object was presented to the monkey. This object was also jiggled for 5 s and then placed into the other slot behind the screen that covered it. The experimenter again showed the empty hand to the monkey. The screens were then removed to reveal either one object (unexpected outcome) or two objects (expected outcome) behind the screens. As soon as the screens were removed, the experimenter signaled to the observer to begin the 10 s count while recording the amount of time the monkey spent looking at the display. Test trials were administered in one of two orders (1-2 or 2-1). Order of outcome (one object first, two objects first) and side of one object trials (left, right) were counterbalanced across subjects.

Trial type (baseline, test) and outcome (one object, two objects) were within-subjects variables, whereas order (one object first, two objects first) and side of one object trials (left, right) were between-subjects variables.

Looking time data were recorded on video (Panasonic Omnivision S-VHSC PV-S372D) and then coded independently by two experienced observers from the MIT Infant Cognition Laboratory who were blind to the experimental conditions presented. The reliabilities between these observers was 94%. Coding of looking times proceeded exactly the same way for all of the experiments in Part II. Coders employed the following criterion: for each look, the subject had looked at the display for at least 0.5 s cumulatively and then had looked away from the display area for 2 s continuously. Thus, looking time was defined as the cumulative amount of seconds out of a 10 seconds total that the monkey looked at the display area before looking away for more than 2 consecutive seconds.

Data from 8 monkeys were used in the following analyses. Data from 2 remaining monkeys could not be used due to inattention of the subjects during the experiment. Inattention was quantified as looking time less than .5 s in the baseline trials.

Results

Preliminary analyses revealed no effects of either order of outcome (one object first, two objects first) or side of one object trials (left, right). Subsequent analyses were therefore collapsed over these variables.

Figure 6 shows the mean looking times at one and two objects in the baseline and in the test trials. In the baseline trials, 7 out of 8 monkeys looked longer when there were two objects behind the screens than when there was one single object (Baseline: $\underline{M}_{\text{one object}} = 3.35$ s; $\underline{M}_{\text{two objects}} = 4.9$ s.) In the test trials, however, 7 out of 8 monkeys looked longer at the outcome of one object, the unexpected outcome for the 1+1 operation (Test: $\underline{M}_{\text{one object}} = 4.9$ s; $\underline{M}_{\text{two objects}} = 2.57$ s.) (One subject looked exactly equally long at 1 and 2 objects in the test trials.)

Insert Figure 6 about here

Looking times were compared using a 2 x 2 ANOVA with trial type (baseline, test) and outcome (one object, two objects) as within-subject variables. There were no main effects of either trial type or outcome. However, there was an interaction between these two factors: $F(1, 7) = 16.431$, $p < .005$. This interaction suggests that there was a reversal in looking time preference for outcomes between the baseline and the test trials.

Follow-up t-tests revealed no significant difference of looking times at one and two objects in the baseline trials ($p>.10$). However, there was a significant difference between looking times at one and two objects in the test trials ($t(7) = 3.9$, $p<.005$, two-tailed). The monkeys looked significantly longer at the unexpected outcome of one object than at the expected outcome of two objects in the test trials.

Further non-parametric analyses (Wilcoxon signed-rank test, corrected for ties) performed on these data revealed that all 8 subjects showed a stronger looking time preference for the unexpected outcome of one object in the test trials than in the baseline trials (Wilcoxon $Z = -2.52$, $p < .02$).

The main result of this study is that the monkeys had a stronger preference to look at the unexpected outcome of one object in the test trials, overcoming a slight preference for two objects in the baseline trials. Taken together, these data suggest that the monkeys were sensitive to the operation performed behind the screens, and, therefore, expected two objects to be revealed when the screens were removed. These results further show that the preferential looking/violation of expectancy method could be used with non-human primates more distantly related than rhesus monkeys, yielding interpretable data. However, as the procedure used was a split-screen design, no comparison could be drawn between the present results and the previous results with the rhesus.

c. Experiment 4: 1 + 1 = 2 versus 1

Experiment 3 provided evidence that cotton-top tamarins possess similar capacities to add 1 + 1 = 2 in a 1 + 1 = 2 or 1 in a split-screen design. However, all the addition experiments where rhesus monkeys were tested involved single screens, namely, a single screen was placed in front of the experimental apparatus to hide the interior of the box and then objects were placed behind it. To make a direct comparison with the experiments conducted with rhesus monkeys (Part I) and further comparisons with human infants (Chapter II here), we conducted Experiment 4, a single screen version of 1 + 1 = 2 or 1.

Experimental Design

Materials and Apparatus

The testing apparatus was identical to the one used with the rhesus in Part I except for its size. It was a box made of foam core measuring 20 cm x 10 cm x 15 cm. The exterior of it was gray, except for a bright pink front panel. The top was open and the front panel consisted of a removable screen with a concealed cloth pouch on the back side (i.e., according to the monkey's point of view). The stimuli were two identical objects each consisting of three orange Fruit Loops glued together one on top of the other to form a small column. They measured 2 cm in diameter at the base and 1cm high (See Figure 3).

Design and Procedure

The experimental protocol used in this experiment, as well as in the following experiments, was modeled on the experiments of Part I with three differences: 1) The size of the testing apparatus was reduced (although the proportion was maintained) because of the size differences between the species; 2) The kind and properties of the stimuli were also different (eggplants versus Fruit loop composites); and 3) The design concerning both number of trials and presentation of baseline and test trials was changed. As mentioned previously, the design for the tamarin experiments was within-subjects due to the availability of only a fixed number of animals (n = 10), as opposed to the opportunities available by the use of the semi free-ranging rhesus macaques of Cayo, Santiago. In the experiments in Cayo, the monkeys received two familiarization trials and only one test trial. Therefore, each monkey either received the unexpected outcome of one object or the expected outcome of two objects as the test trial. In the present experiments, each monkey received the same four familiarization trials and the same two test trials, counterbalanced across subjects.

The experiment consisted of the same 3 phases as described in Experiment 3. Phase I was a familiarization condition that served to acquaint the subject with the testing apparatus and the objects used as stimuli. Phase II was a baseline condition which served to introduce the subject to the lowering of objects into the box, the raising and lowering of the screen, and the fact that objects lowered into a hidden location are later found in that location. The baseline trials also served to obtain a measure of the subject's preference for one-object arrays as opposed to two-object arrays. Phase III consisted of two test trials, one with the expected outcome and one with the unexpected outcome. As in Experiment 1, each session took approximately 5 minutes to run. The subjects were given 1/4 of a Fruit Loop after each pair of trials. Familiarization and test trials are illustrated in Figure 2.

Familiarization phase. As in Experiment 3, every monkey was given a 30 s exposure to the apparatus and the objects before the experiment began: the experimenter drew the attention of the monkey to the empty box by jiggling one object in front of the monkey's eyes and then bringing it towards the empty screenless box. The experimenter then brought the object towards the front panel of the testing chamber and held it there until the monkey looked at it for at least 2 s.

Baseline phase. There were two pairs of baseline trials -- each pair consisting of a single object trial and a double object trial. The procedure for the first pair of baseline trials was the same as that of the baseline trials described for Experiment 1, except that objects were placed on the floor of the box rather than in slots. For the second pair of baseline trials, a single screen was placed to hide the interior of the testing box, and the objects were lowered behind the screen. Baseline trials alternated between one and two object outcomes in two orders (1-2-2-1 or 2-1-1-2). The pair of trials without a screen always preceded the trials with a screen. Order of outcome (one object first, two objects first) and side of one object trials (left, right) were counterbalanced across subjects.

Test phase. There were two test trials which immediately followed the baseline phase -- each consisting of a single object trial and a double object trial. The procedure for the test trials was the same as that of the test trials described for Experiment 1. Test trials were administered in one of two orders (1-2 or 2-1). Order of outcome (one object first, two objects first) and side of one object trials (left, right) were counterbalanced across subjects.

Trial type (baseline, test) and outcome (one object, two objects) were within-subjects variables, whereas order (one object first, two objects first) and side of one object trials (left, right) were between-subject variables.

We used the same recording procedure as described for Experiment 3. The same two experienced observers separately coded the looking times. They were blind to the experimental conditions presented. The reliabilities between these observers was 91%. Looking time data from 8 monkeys were used in the following analyses. Data from 2 monkeys could not be used due to inattention of the subjects during the experiment. Note that the monkeys excluded from this study were different from the ones excluded in the previous experiment. Any monkey can get upset or tired during the session and not attend to the experimental condition. It is not the case that the same monkeys are discarded in all of these experiments.

Results

Preliminary analyses revealed no effects of either order of outcome (one object first, two objects first) or side of one object trials (left, right). Subsequent analyses were therefore collapsed over these variables.

Figure 7 shows the mean looking times at one and two objects in the baseline and in the test trials. During the baseline trials, all the monkeys looked longer when there were two objects behind the screen than when there was only one object (Baseline: $\underline{M}_{\text{one object}} =$ 2.27 s.; $\underline{M}_{\text{two objects}} =$ 4.21 s.). During the test trials, in contrast, 7 out of 8 monkeys looked longer at the outcome of one object, which would be the unexpected outcome for the addition of 1+1 (Test: $\underline{M}_{\text{one object}} =$ 2.13 s.; $\underline{M}_{\text{two objects}} =$ 1.55 s.).

Insert Figure 7 about here

A 2 x 2 ANOVA performed on these data examined the effects of trial type (baseline, test) and outcome (one object, two objects) as within-subject variables. There was a main effect of trial type (baseline, test): $F(1,7) = 13.254$, $p < .008$. The monkeys looked longer at the baseline trials ($\underline{M}_{\text{Baseline}} = 3.24$ s) than at the test trials ($\underline{M}_{\text{Test}} = 1.84$ s). There was also a main effect of outcome (one object, two objects): $F(1,7) = 21.608$, $p < .002$, namely, looking times to two objects ($\underline{M}_{\text{Two objects}} = 2.88$ s) were significantly longer than the looking times to one object ($\underline{M}_{\text{One object}} = 2.2$ s). Most importantly, there was a statistically significant interaction between these two variables: $F(1, 7) = 44.054$, $p < .0001$.

This interaction was examined using follow-up t-tests. These tests revealed that subjects looked significantly longer at two objects than at one object in the baseline trials ($t(7) = -3.7$, $p < .008$, two-tailed) but looked significantly longer at one object than at two objects in the test trials ($t(7) = 2.6$, $p < .04$, two-tailed). Thus, the preference for looking at two objects in the baseline trials was reversed in the test trials, on which there was looking time preference for the unexpected outcome of one object.

Further non-parametric analyses (Wilcoxon signed-rank test, corrected for ties) performed on those data revealed that 7 of the 8 monkeys showed a stronger preference for the unexpected outcome of one object in the test trials than in the baseline trials (Wilcoxon $Z = -2.38$, $p < .02$). In sum, the monkeys were sensitive to the successive placement of one, and then another, object behind the screen, and expected two objects upon its removal.

The results of Experiment 4 add to those of Experiment 3 in that the tamarins looked longer at the unexpected outcome of one object even when the addition operation was performed behind one single screen. Just like Experiment 3, where separate screens helped the monkeys individuate distinct objects and set up expectations about the number of objects to be behind the screen, this experiment required them to set up representations of two distinct objects behind a single screen.

d. Experiment 5: 1 + 1 = 2 versus 3

The data from Experiments 3 and 4 with cotton-top tamarins replicated the pattern of results of the addition experiment of Hauser et al. (1996) with rhesus monkeys, namely, the tamarins interpreted the addition operation as involving two distinct objects and looked longer at the unexpected outcome of one object. However, success in these 1 + 1 = 2 or 1 tasks does not necessarily mean that the tamarins expected to see exactly two objects behind the screen.

It is also possible that the tamarins had no understanding of what the precise outcome for the addition of 1 + 1 should be. As in the rhesus monkeys' case, there are alternative interpretations of the tamarin results. First, it may be the case that the monkeys succeeded in 1 + 1 tasks because they formed expectations to see a numerical change from one object to something else in the outcome -- that is, the monkeys might expect to see something different from one in the outcome of the 1 + 1 operation. Second, it might also be the case that the monkeys succeeded in 1 + 1 tasks because they expected to see more than one object behind the screen, but not necessarily exactly two.

Experiment 5 was conducted to rule out these alternative hypotheses. If the monkeys set up expectations for exactly two objects as the result of the 1 + 1 operation and not for a numerical change in what is behind the screen, or for more than one object, then they should succeed by looking longer when they see three objects rather than two in the box.

Experimental Design

Materials and Apparatus

The testing apparatus used in this experiment was the same one as described in Experiment 4. The box was gray with a bright green screen. The stimuli were three identical objects each consisting of four yellow Fruit Loops glued together one on top of the other to form a column. They measured 2 cm in diameter at the base and 2 cm high (See Figure 3).

Design and Procedure

The procedure and design of this experiment were identical to those outlined for Experiment 4, with the exception that the number of objects used in the familiarization and test trials was different.

The experiment consisted of exactly the same 3 phases as described in Experiment 4, except that, in the unexpected outcome trials, three objects were presented as the "unexpected" result of the 1 + 1 operation. Baseline trials alternated between two and three object outcomes in two orders (3-2-2-3 or 2-3-3-2). The pair of trials without a screen always preceded the trials with a screen. Order of outcome (three objects first, two objects first) was counterbalanced across subjects[4]. Test trials were administered in one of two orders (3-2 or 2-3). Order of outcome (three objects first, two objects first) was counterbalanced across subjects. Figure 2 illustrates the familiarization and test trials of this experiment.

Trial type (baseline, test) and outcome (three objects, two objects) were within subjects variables, whereas order (three objects first, two objects first) was a between-subjects variable.

The same recording and scoring tools described in Experiment 3 were used here. The same two experienced observers separately coded the looking times. These observers were blind to the experimental conditions presented. The reliabilities between these observers was 91%. Looking time data from 8 monkeys were used in the following analyses. Data from 2 monkeys could not be used due to inattention of the subjects during the experiment.

Results

Preliminary analyses revealed no effects of order of outcome (three objects first, two objects first) . Subsequent analyses were therefore collapsed over this variable.

Figure 8 shows the mean looking times at two and three objects in the baseline and in the test trials. In both the baseline and the test trials, 7 of the 8 monkeys looked longer when there were three objects than when there were two behind the screen (Baseline: $\underline{M}_{\text{two objects}} = 1.81$ s.; $\underline{M}_{\text{three objects}} = 2.45$ s.; Test: $\underline{M}_{\text{two objects}} = 1.17$ s.; $\underline{M}_{\text{three objects}} = 2.42$ s.).

Insert Figure 8 about here

Looking times were compared using a 2 x 2 ANOVA with trial type (baseline, test) and outcome (two objects, three objects) as within-subject variables. There was no main effect of trial type (baseline, test). However, there was a main effect of outcome: $F(1, 7) = 94.610$, $p < .0001$, showing that monkeys looked longer overall at three objects than at two objects. Moreover, and more importantly, there was a trial type x outcome interaction: $F(1, 7) = 6.983$, $p < .04$. This interaction is revealing because it suggests that, despite the monkeys' overall preference to look at three objects in both baseline and test trials, there is a stronger preference to look at the outcome of three objects (unexpected) in the test trials than in the baseline trials.

In order to further test this interaction, follow-up t-tests compared the looking times to two and three objects in the baseline and in the test trials. These tests revealed that looking times to two and three objects were significantly different both in the baseline (t (7) = -6.5, p < .0003, two-tailed) and in the test trials (t (7) = -6.6, p < .0003, two-tailed). Thus, according to the parametric tests, while looking times to two and three objects were significantly different, the interaction revealed a stronger preference for three objects in the test trials than in the baseline trials.

The pattern suggested by the interaction in the 2 x 2 ANOVA was confirmed by non-parametric tests (Wilcoxon signed-rank test corrected for ties) which revealed that 7 of the 8 monkeys showed a stronger preference for the unexpected outcome of three objects in the test trials than in the baseline trials (Wilcoxon Z = -2.32, p < .02).

Taken together, these data show that monkeys looked longer overall at three objects. This pattern was expected, since three objects is more to look at than two objects. However, the interaction between trial type and outcome shows that the monkeys not only looked attentively to three objects over two objects overall but increased that preference in the test trials.

Experiment 6: 1 + 1 = 2 versus big 1

The tamarins' successes in all 1 + 1 addition tasks may suggest that they did expect to see two objects behind the screen upon its removal. However, as suggested before, it may also be the case that the monkeys were encoding information on the basis of amount of stuff. For example, the tamarins might have looked longer at the unexpected outcomes, not because there were either more or less individual objects than were observed being placed behind the screen. Rather, subjects might have attended to the amount of Fruit loop stuff in the display.

As in Experiment 4, this experiment seeks to provide evidence that rules out the amount of stuff hypotheses. Here, differently from the rhesus study, we do not present an object that was roughly double the volume of one small Fruit loop composite, as the eggplant was roughly the double the volume of a small one. In the present experiment, the monkeys were familiarized with a composite Fruit loop that was double the volume and also roughly double the amount of surface area. This big 1 object was composed of a column of Fruit loops arranged as double the height of the little composite that constituted one of the stimuli. Note that, by constructing this object, we are in the position to fulfill two objectives: 1) Test a hypothesis that the monkeys are encoding amount of Fruit loop stuff in terms of volume; and 2) Test a hypothesis that the monkeys are encoding amount of stuff in terms of surface area. If the monkeys are only expecting consistency in the volume of Fruit loop stuff or consistency in the amount of surface area of Fruit loop stuff in the display then they should show either no change or a decline in looking time. In contrast, if subjects are individuating the actual objects in the arrays, then they should look longer if they see a single big 1 Fruit loop object (unexpected) than if they see two smaller Fruit loop objects (expected).

Experimental Design

Materials and Apparatus

The testing apparatus used in this experiment was the same one as described in Experiments 4 and 5. The box was gray with a bright green screen. The stimuli were two identical small objects each consisting of two pink Fruit Loops glued together one on top of the other to form a column. Two of the objects measured 2 cm in diameter at the base and

1.5 cm high. The big 1 object consisted of four Fruit loops glued one on top of the other and it measured 2 cm in diameter at the base and 3 cm high (See Figure 3).

Design and Procedure

The procedure and design of this experiment were identical to the ones outlined for Experiments 4 and 5, with the exception that the number of objects used in the familiarization and test trials was different.

The experiment consisted of exactly the same 3 phases as described in Experiment 4, except that, in the unexpected outcome trials, a big-one object was presented as the "unexpected" result of the 1 + 1 operation. In this experiment, both for the familiarization and for the test trials, the big-one object was always placed in the center of the box. Therefore, differently from 1 + 1 = 2 or 1 experiments, there was no "side of one-object outcome" variable to look at. The two-object outcome followed the same arrangement as in previous experiments. Familiarization and test trials are illustrated in Figure 2.

Baseline trials alternated between big-one-object and two-object outcomes in two orders (big 1-2-2-big 1 or 2-big 1-big 1-2). The pair of trials without a screen always preceded the pair of trials with a screen. Order of outcome (one big object first, two objects first) was counterbalanced across subjects. Test trials were administered in one of two orders (big 1-2 or 2-big 1). Order of outcome (three objects first, two objects first) was counterbalanced across subjects.

Trial type (baseline, test) and outcome (big-one object, two objects) were within subjects variables, whereas order (big-one object first, two objects first) and side of one object trials (left, right) were between-subjects variables.

The same recording and scoring tools described in Experiment 3 were used here. The same two experienced observers separately coded the looking times. These observers were blind to the experimental conditions presented. The reliabilities between these observers was 90%. Looking time data from 9 monkeys were used in the following analyses. Data from 1 monkey could not be used due to inattention of the subject during the experiment.

Results

Preliminary analyses revealed no effects of order of outcome (big-one object first, two objects first). Subsequent analyses were therefore collapsed over this variable.

Figure 9 shows the mean looking times at one big object and two objects in the baseline and in the test trials. In the baseline trials, 7 of the 9 monkeys looked longer when there were two small objects ($\underline{M}_{\text{two objects}} = 2.1$ s.) behind the screen than when there was the big-one object ($\underline{M}_{\text{big one object}} = 1.28$ s.). In the test trials, 8 out of 9 monkeys looked longer at the outcome of the big-one object, which would be the unexpected outcome for the addition of 1+1 (Test: $\underline{M}_{\text{two objects}} = 1.54$ s.; $\underline{M}_{\text{big one object}} = 2.35$ s.).

Insert Figure 9 about here

A 2 x 2 ANOVA examined the effects of trial type (baseline, test) and outcome (big-one object, two objects) on looking times. There was no main effect of trial type (baseline, test) or outcome (big-one object, two objects). However, there was an interaction between these two variables: $F(1, 8) = 10.274$, $p < .02$. Follow-up t-tests revealed that looking times were significantly different both in the baseline trials ($t(8) = -2.9$, $p < .03$, two-tailed) and in the test trials ($t(8) = 2.5$, $p < .04$, two-tailed). The monkeys looked significantly longer at two objects than at one object in the baseline trials, whereas they looked significantly longer at one object than at two objects in the test trials. In sum, the interaction reflects the preference for looking at two objects in the baseline trials and the reversal of this pattern in the test trials.

This pattern was confirmed by a Wilcoxon signed-rank test (corrected for ties) which revealed that 8 of the 9 monkeys showed a stronger preference for the unexpected outcome of one big object in the test trials than in the baseline trials (Wilcoxon Z = -2.31, p = .02).

Discussion

Experiment 6 ruled out the amount of stuff hypotheses. The results suggest that the tamarins individuated the actual objects in the arrays. They looked longer when they saw a single big 1 Fruit loop object (unexpected outcome) than when they saw two smaller Fruit loop objects (expected outcome). Thus, it is possible that they did not represent objects in the arrays on the basis of consistency in the volume or amount of surface area of Fruit loop stuff in the display. The fact that they looked longer at two objects than at one big object in the baseline trials is also suggestive. If they were encoding amount of stuff, then they would perhaps look roughly equally at both the two-object display and at the big-one object display, which was not the case.

However, it is possible that the tamarins, as well as the rhesus monkeys, looked longer at the big 1 object because of property disparity, namely, shape differences between the objects they saw going behind the screen and the big 1 object. It can be argued that both the rhesus and the tamarins looked longer at the big 1 object in the test trials not because they necessarily expected to see two objects but because they saw a certain shape go behind the screen and set up an expectation to see that shape appear upon removal of the screen. Once they saw a different shape, they looked longer at the big 1 object than at two objects. Therefore, the property differences between the objects could have been the factor underlying their longer looking at the big 1 object. One way to address this question would be to conduct an experiment in which the results of the addition 1 + 1 operation were (1) two big objects or (2) one big object -- both impossible outcomes for the addition operation. This way, keeping the property of the outcomes constant and varying number of objects, the monkeys would be forced to choose between outcomes where the properties of the objects were dissimilar from the ones of the objects presented in the addition operation.

General Discussion

These experiments provide evidence that nonhuman primates present spontaneous rudimentary numerical representations, comparable to human infants. Both rhesus monkeys and cotton-top tamarins succeed in a wide variety of in 1 + 1 tasks. The results with the rhesus macaques (Part I) extend the results of Hauser et al. (1996) demonstrating that rhesus monkeys have the understanding of the addition operation. The monkeys were able to individuate the actual objects in the box and set up expectations for number of objects to be behind the screen. The experiments with cotton-top tamarins (Part II) were devised to test for these abilities in a species much more distant, evolutionarily, from humans than are rhesus macaques. The results show that the tamarins also set up the representations of the objects in the arrays and expected to see a determined number of objects when the screen was removed.

In order to compare the spontaneous numerical capacities of nonlinguistic primates to that of prelinguistic infants, the preferential looking/violation of expectancy technique was utilized and shown to be successful both in a population of semi-free-ranging rhesus macaques and with a population (n = 10) of laboratory cotton-top tamarins, a more distantly related species than are rhesus macaques. The cotton-top tamarins payed attention to the events when they were being presented. In addition, the monkeys were shown to understand the addition events and to set up the correct expectancies. The results of these experiments, together with those of Hauser et al. (1996), are suggestive that the rudimentary numerical abilities present in young human infants are widely shared among primates.

These results go further than published work on addition experiments with human infants. They demonstrate that the monkeys were seemingly not encoding information about the objects based on "amount of stuff" or "amount of surface area". The big one experiment is an innovation and was devised to test for the aforementioned hypotheses. However, it is still possible that the monkeys looked longer at the big one object (Experiment 2 with rhesus and Experiment 6 with tamarins) because they were encoding the properties of the objects that disappeared behind the screen rather than the number of objects. That is, they saw two objects each with a certain size go behind the screen and they looked longer at the big object not because they were expecting two objects they had previously seen but because the big one object did not have the same properties they had previously encoded (property disparity). As suggested before, an experiment in which the property differences (but not the number of objects) are held constant in the outcomes is suggested as a further development of the present study.

In adapting the design to the lab population, methodological problems such as 1) changing a between-subjects design into a within-subjects design; 2) finding the appropriate stimuli that would keep the monkey within task; or 3) risking lose the monkeys' interest due to overtesting were solved. One advantage of the use of this technique with lab animals over human infants is that the studies can be more carefully controlled for experimental effects. The laboratory situation of the animals, on the one hand, allows for the control of the experience the animals undergo along testing. For example, experimenters in the lab know exactly the experiments, amount of training, and performance data of each individual, which can be useful to observe individual differences, individual experience, group experience and patterns of successes and failures. In the case of human infants, on the other hand, there is no possible means to control for such aspects.

The relevance of the present studies also lies in the fact that a larger sample of the species populations (than usually is the case) was investigated, contrary to the majority of the studies with nonhuman primates on numerical abilities. Over 90% of the literature on nonhuman primates' numerical abilities investigate solely one or two animals -- Boysen's Sheba, Matsuzawa's Ai, Rumbaugh's Sherman and Austin. Researchers base their conclusions on these findings and tend to generalize the cognitive abilities found with this sample to the species. Although results with one or two chimpanzees are interesting in themselves and may imply that the capacity constitutes part of the genetic endowment of the particular species,.the results may not necessarily reflect abilities that can be generalized as accounting for an entire population (Boysen, 1994).

A further importance of this investigation with more distantly related species than apes regards the possibility of expanding the characterization of cognitive primitives beyond the realm of the chimpanzee. The majority of the studies in comparative cognition have been performed with chimpanzees because, at first, it was believed that chimpanzees were putatively the smartest of all nonhuman primate species. Investigations with such a species would allow researchers to find correlates between their capabilities and our own (Ferster, 1964). More recently, with the advent of genetic research, chimpanzees have been shown to be the closest related species to humans, sharing with us 95% of their genetic code (Sibley & Ahlquist, 1984). It seems, thus, that putative intelligence and phylogenetic proximity have impelled a vast amount of research with chimpanzees, addressing questions which range from linguistic abilities (Gardner & Gardner, 1969, 1975; Premack, 1970; Savage-Rumbaugh, Rumbaugh & Boysen, 1980; Terrace, Pettito, Sanders & Bever, 1979), theory of mind (Woodruff & Premack, 1981), to numerical abilities (Boysen, 1993; Matsuzawa, 1985; Washburn & Rumbaugh, 1991), in the realm of cognitive research.

However, researchers in comparative psychology commonly claim that the inherited architecture of the human mind is a product of the evolutionary process (Byrne & Whiten, 1988; Cheney & Seyfarth, 1990; Gallistel, 1990; Gallistel & Gelman, 1992; Klein & Starkey, 1987; Povinelli, 1993; Povinelli & Eddy, 1996; Premack, 1976). If this is so, then presumably one would expect to find certain cognitive primitives in even very distantly related species. In particular, the question addressed here is when in the evolutionary process precursors to human numerical knowledge were born. If human capabilities present in early infancy can be shown in species as distant as tamarins, then presumably such abilities are widely shared and can perhaps be considered as cognitive primitives in phylogeny (Hauser & Carey, in press). The findings suggest that primates as distant as cotton-top tamarins present the same primitive spontaneous numerical abilities that do human infants.

Attempts to understand the ecological validity of certain cognitive abilities in animals have proliferated in the animal behavior field, especially amongst ethologists (Koehler, 1949; Harper, 1982). As suggested by Gallistel (1990), it would be rather surprising if animals in general lacked some kind of way of roughly calculating or estimating, for example, the amount of food in their natural environment. Harper (1982), for example, showed that a flock of 33 free-living mallards would distribute themselves between two patches of food in equilibrium, roughly estimating the frequency of supply of food items to assess profitability. Two experimenters positioned on opposite sides of a lake distributed food items weighing 2 g at a rate of 1 item/5 seconds at a ratio of 1:1, namely, both sites delivered the same amount of food available. If the mallards were estimating the quantity of food available in both sites, the number of animals in each site should be roughly 16 1/2. In approximately one minute, the number of animals in each group was 16 +/- 2. This is evidence that the ducks can spontaneously encode amount of stuff and estimate this amount of stuff available to the population. Sensitivity to number seems to be spontaneously available to a variety of species, one of the reasons being perhaps its ecological relevance. The present experiments add to the picture of animal numerical capacities, among other things, because they show that the representations being tapped by this experimental paradigm are spontaneously available.

Different types of numerical representations have been shown in nonhuman primates. In this literature, it is difficult to separate whether the capacities tapped by the training experiments are genuinely numerical or whether they are dependent upon task specific requirements. In the first case, it may be that the nonhuman primates, in particular, the chimpanzees, at the end of the training experiments, possess numerical representations -- that is, they map on a one-to-one correspondence basis the numerosity of the set with a symbol and they can add different sets of objects. It is very likely that Sheba (Boysen 1993), for example, does. In the second case, it may also be that the animals develop strategies to solve the tasks. In the number discrimination tasks with rhesus macaques (Thomas & Chase, 1980; Washburn & Rumbaugh, 1991), for example, it can be argued that all the monkeys are doing is pattern discrimination and association attribution.

Despite this training, it is extremely hard for animals to learn the symbolic numerical system. It usually takes months or even years of intensive training for the animals to arrive at number discrimination (Ferster, 1964); ordinal relationships (Washburn & Rumbaugh, 1991); summation (Rumbaugh, Savage-Rumbaugh & Hegel, 1987), number assignment through symbolic tagging (Matsuzawa, 1985; Boysen, 1993) and addition (Boysen, 1993). The chimpanzees' symbolic representation of number seems to depend on the long and hard process of training. However, given the present results, and given that chimpanzees are the closest related species to humans, there is no reason to doubt that chimpanzees have at least the same spontaneous capacities as do rhesus monkeys and tamarins.

It seems certain, thus, that spontaneous numerical representations are available not only to humans. The present findings are suggestive that number is not fundamentally tied to the human language faculty. At least two species of nonlinguistic nonhuman primates present spontaneous representations comparable to those of prelinguistic human infants. If spontaneous representations of number are available to nonhuman primates as distantly related to humans as rhesus monkeys and cotton-top tamarins, then why do the chimpanzees need so much training to arrive at a symbolic representation of number?

A first possibility regards the fact that the training process that chimpanzees are submitted to is different than the one human child naturally undergoes. The chimpanzees are trained at distinct numerosities, one at a time, in an incremental pattern, that is, they learn that "1" corresponds to oneness, "2" corresponds to twoness, "3" corresponds to threeness, and so forth and so on (Matsuzawa, 1985; Boysen & Berntson, 1989; Boysen, 1993) The training regime of the chimpanzees never presents the list of tags corresponding to the numerosities as a whole, as would be the case with human children. Children learn the list first, where the number words map onto the numerosities in an ordered fashion. For example, a child may count "one, two, six, seven, nine", and mean "one, two, three, four, five" in a consistent way. The child then later on learns that each symbol in language has a numerical meaning. They understand, at first, what "one" means, then what "two" means, and then "three", and then "four", etc (Wynn, 1992). Once they have worked out what the beginning of the list is, they start understanding that each word in the number list relates to a meaningful numerosity that increases by one. This induction process is worked out so the child arrives at the understanding that the number words correspond to determined numerosities. It may be that the fact that the chimpanzees do not have the list onto which numerosities map makes it harder for them to learn the symbolic representation because they have to learn the mapping at each time a new numerosity is introduced to them instead of having internalized a counting routine that will help them figure out the relationships between the numerosities.

A second possibility is that the establishment of the mapping between the mental symbol and the symbolic representative is a difficult accomplishment. This process is hard for the chimpanzee because she lacks the language faculty. It is hard for the human child to learn to assign linguistic tags to the numerosities. However, the child learns the linguistic representative more easily than chimpanzees because the generativity of language allows him to generate the list. At first, the child establishes the one-one mapping between the numerosities and the linguistic representatives. Once this is established, the child needs to work out that the linguistic list is meaningful and that for each symbol in language there is a corresponding mental symbol that, in turn, corresponds to actual numerosities. It is this linguistic mapping that the child works so hard at until approximately age 3 1/2. It may be that the chimpanzee is working at the assignment of numerosity to mental symbol to symbolic tag, at each time a new numerosity is presented. This process is effortful and hard because there is no generative system underlying her representational capacity, which needs to be constructed at each step.

Along the same lines, for the chimpanzee, learning to symbolically tag the mental symbols to symbols in the world is just artificial, lacking in natural or species-specific quality. It may simply be that, for the human child, by virtue of the fact that she is a linguistic creature, the process is easier because it is a natural acquisition, whereas in the case of the chimpanzee, it is not as ecologically relevant. Although the chimpanzees may come to develop a numeron-type of number representation, much the same way human children do, it is unlikely that they will ever spontaneously generalize what number comes next in the counting list, as there is no evidence that chimpanzees reach an understanding that there can be more numbers generated after the number just learned. It seems unlikely that chimpanzees will ever reach the stage of a generative numeron system such as the one underlying the human numerical representational system.

Alternatively, it is possible that different computational resources other than language are being used. It is possible that the human cognitive system differs substantially from the one of nonhuman primates, as it is possible that the cognitive system of humans allows for more flexibility in terms of allowing for combinations of different domains or cognitive modules. For example, both humans and nonhuman primates may possibly have the capacity to open object files in order to account for the representation of number of objects in their world. This representation may get mapped onto an accumulator-type of mechanism, that analog represents the numerosities encountered. Later on, in the case of human children, this representation is mapped onto the numeron system, which in its turn gets mapped onto the linguistic expression of number. In the case of the chimpanzee, it is possible that the animals have an analog-type of representation à la accumulator, and this representation gets mapped onto symbols in the same way the monkeys learn the discrimination between numerical symbols, perhaps by association. This is very speculative and reflects the efforts toward an clearer understanding of the problem.

The pattern of successes obtained with rhesus monkeys and tamarins in this study, combined with the rhesus results of Hauser et al. (1996), show that spontaneous rudimentary numerical capacities are widely shared among primates. These results are enlightening and represent a unique contribution to the study of cognitive abilities in nonhuman primates. The present study opens up a fruitful opportunity for the development of research in comparative cognition work with nonhuman primate species.

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Footnotes

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1 The first 1 + 1 = 2 versus 1 + 1 = 1 task conducted by Hauser et al. (1996) consisted of familiarization and test trials presented in a completely between-subjects design. The monkeys received familiarization or test trials in which the outcomes were 1 or 2 objects, namely, each monkey received only one trial, that is, monkeys saw either a familiarization trial of 1 object, or of 2 objects, or a test trial of 1 object or of 2 objects. It was only after this first experiment that they found that the monkeys would sit longer through experimental sessions. They decided to present the monkeys with a design that included 2 familiarization trials and one test trial following the same counterbalance as for Experiment 1. The two experiments reported here mirrored Experiment 2 of Hauser et al. (1996).

2 Note that twice the volume does not necessarily entail the double amount of surface area. That is, an eggplant that is roughly the same volume of two small eggplants put together is less surface area than the two small eggplants presented separately. In this regard, the present experiment seeks to rule out a hypothesis that the monkeys are encoding amount of stuff based on volume.

3 Fruit Loops are small colorful rings of sweet cereal made for children available in any supermarket; they have been used in the lab as treats for the tamarins.

4 In this experiment, the outcomes of the addition operation were either two objects (expected) or three objects (unexpected) both in the baseline and in the test trials. Differently from all other 1 + 1 = 2 or 1 tasks, where the unexpected outcomes of one object were counterbalanced betweeen left and right sides, here there was no need for counterbalancing insofar as in the three-object outcomes, the third object was always placed in the middle of the other two objects, in the center of the box. Therefore, the variable side of one-object outcome was non-existant. The two-object outcomes followed the same arrangement as in previous experiments.

Figure Captions

Figure 1. Schematic drawings of familiarization and test trials for experiments of Part I.

Figure 2. Mean looking times for two and three objects in baseline and test trials of Experiment 1.

Figure 3. Mean looking times for two and big 1 objects in baseline and test trials of Experiment 2.

Figure 4. Schematic drawings of familiarization and test trials for experiments of Part II.

Figure 5. Schematic drawings of stimuli for experiments in Part II.

Figure 6. Mean looking times for one and two objects in baseline and test trials of Experiment 3.

Figure 7. Mean looking times for one and two objects in baseline and test trials of Experiment 4.

Figure 8. Mean looking times for two and three objects in baseline and test trials of Experiment 5.

Figure 9. Mean looking times for two and big 1 objects in baseline and test trials of Experiment 6.

1 + 1 = 2 versus 1 + 1 = 3

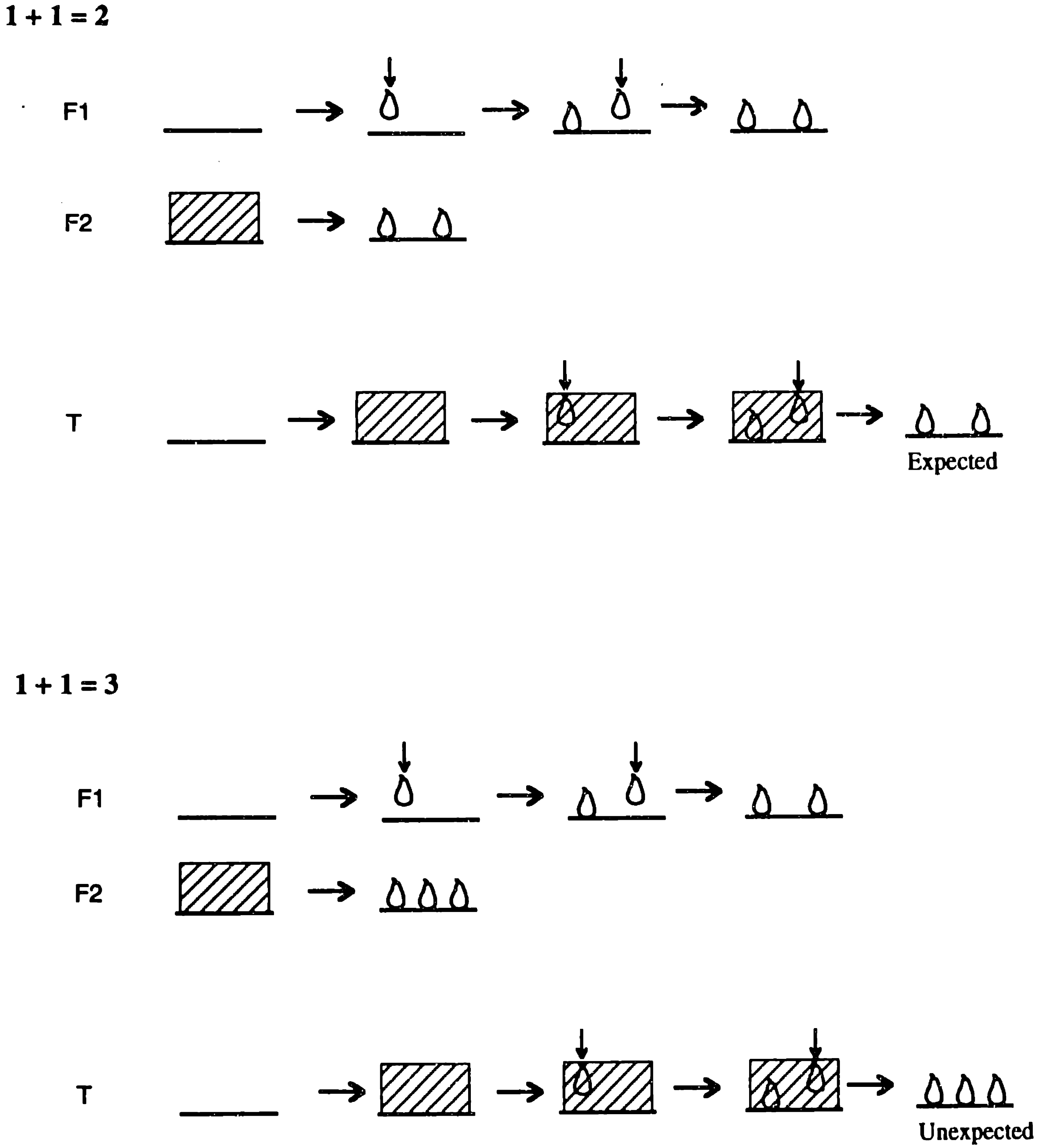


Figure 1

1 + 1 = 2 versus 1 + 1 = Big 1

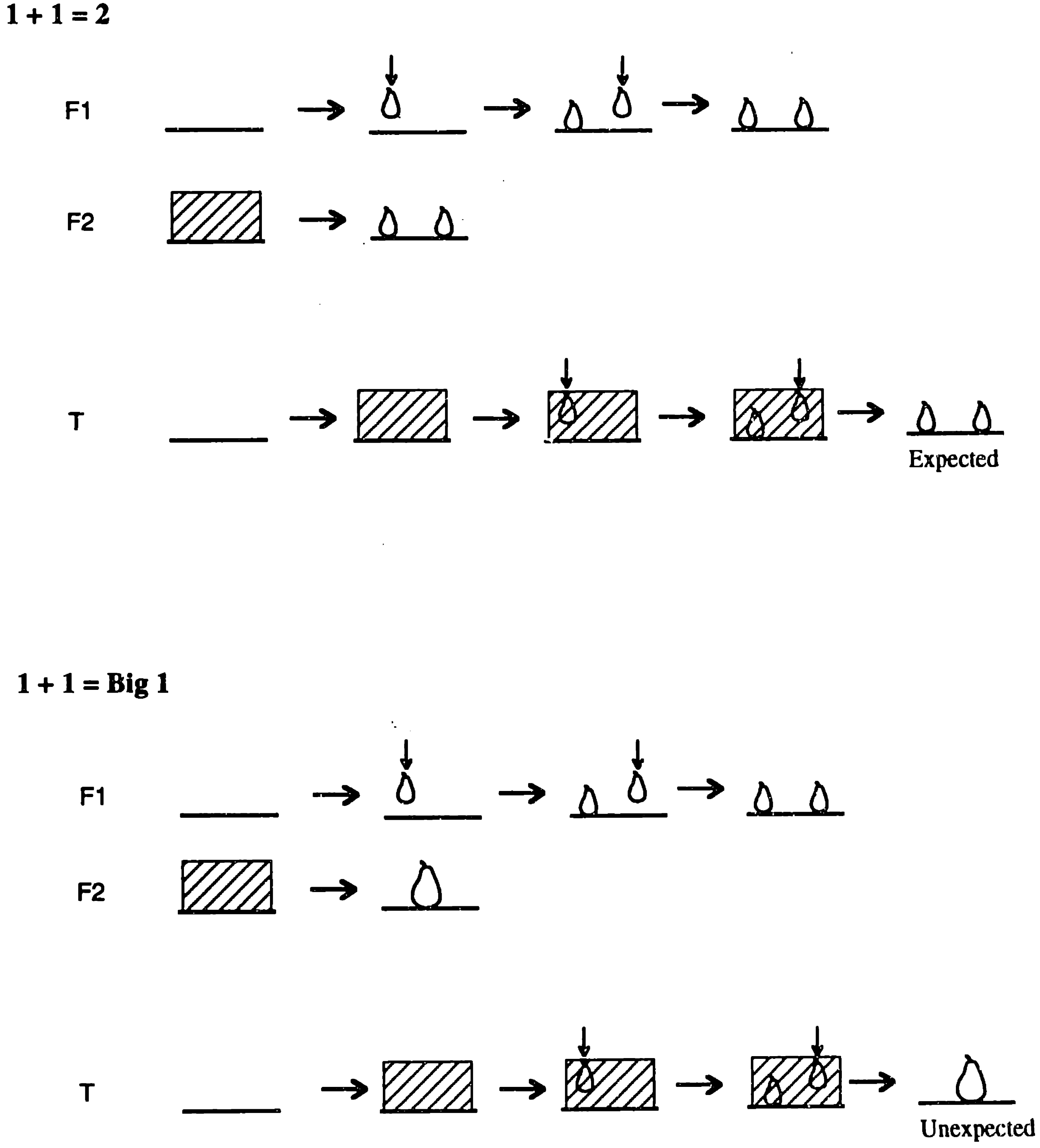


Figure 1

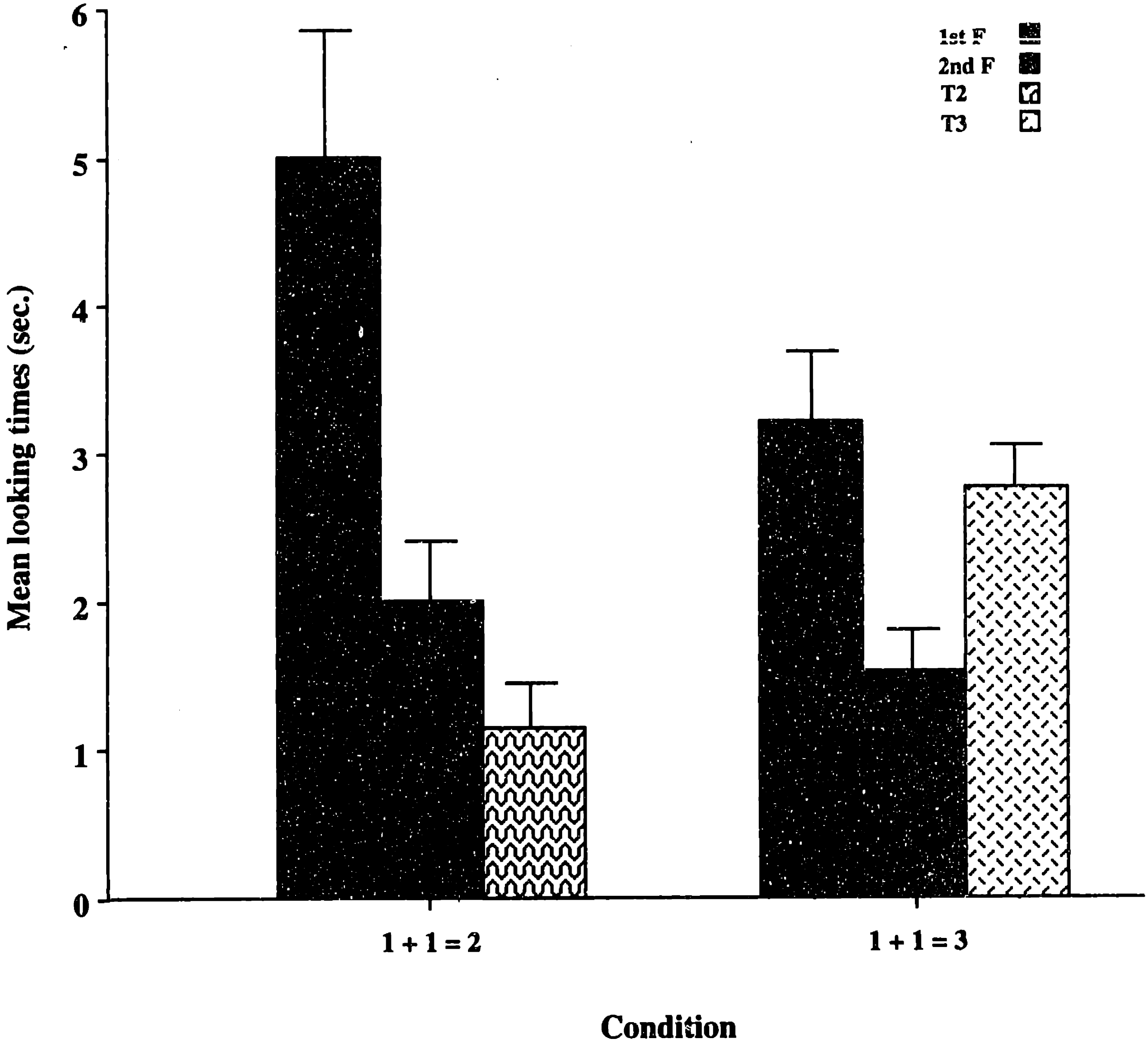

6
5
4
3
2
1
0
Mean looking times (sec.)
1st F
2nd F
T2
T3
1 + 1 = 2
1 + 1 = 3
Condition

Figure 2

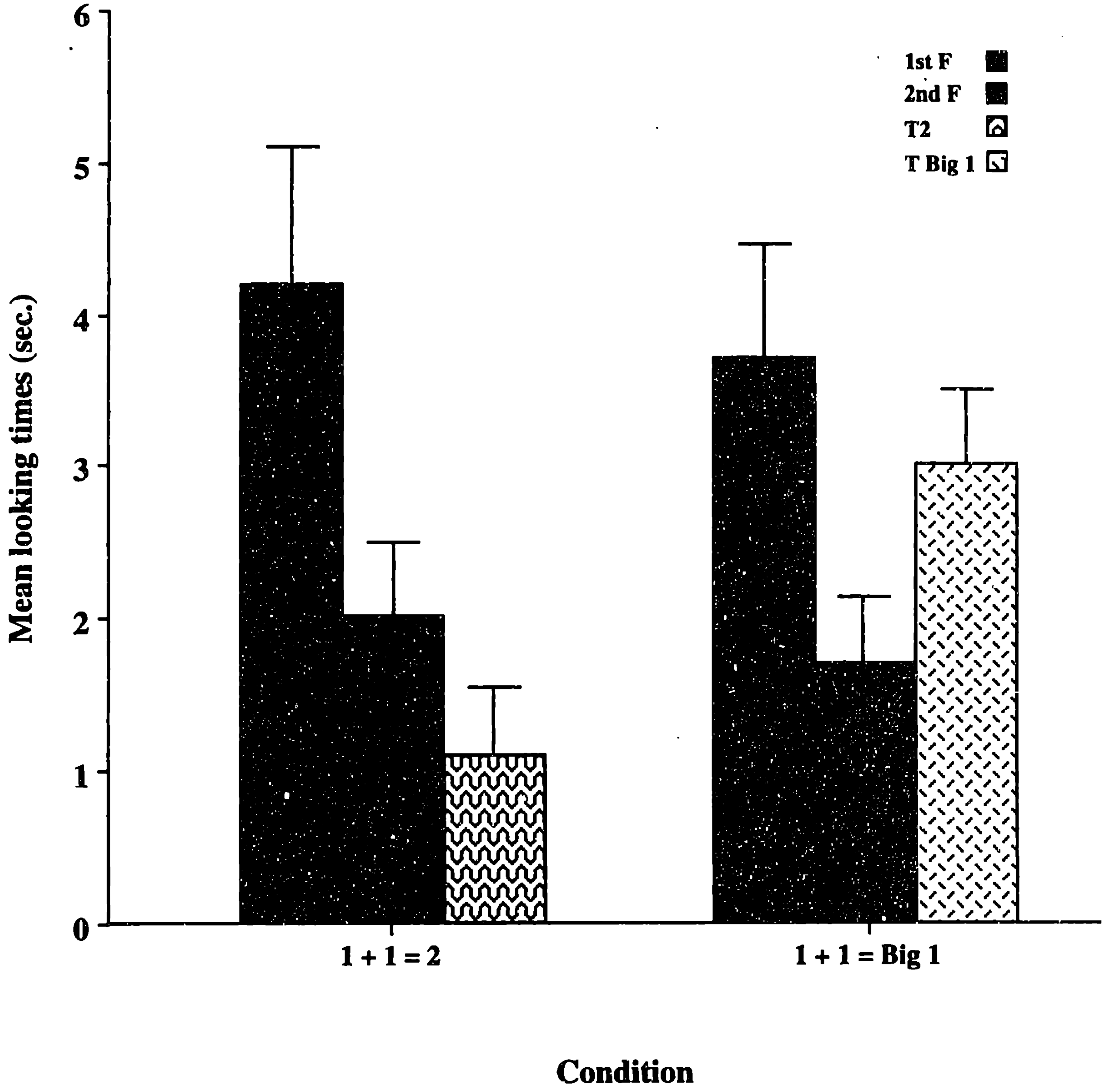

Mean looking times (sec.)
0
1
2
3
4
5
6
1st F
2nd F
T2
T Big 1
1 + 1 = 2
1 + 1 = Big 1
Condition

Figure 3

1 + 1 = 2 versus 1

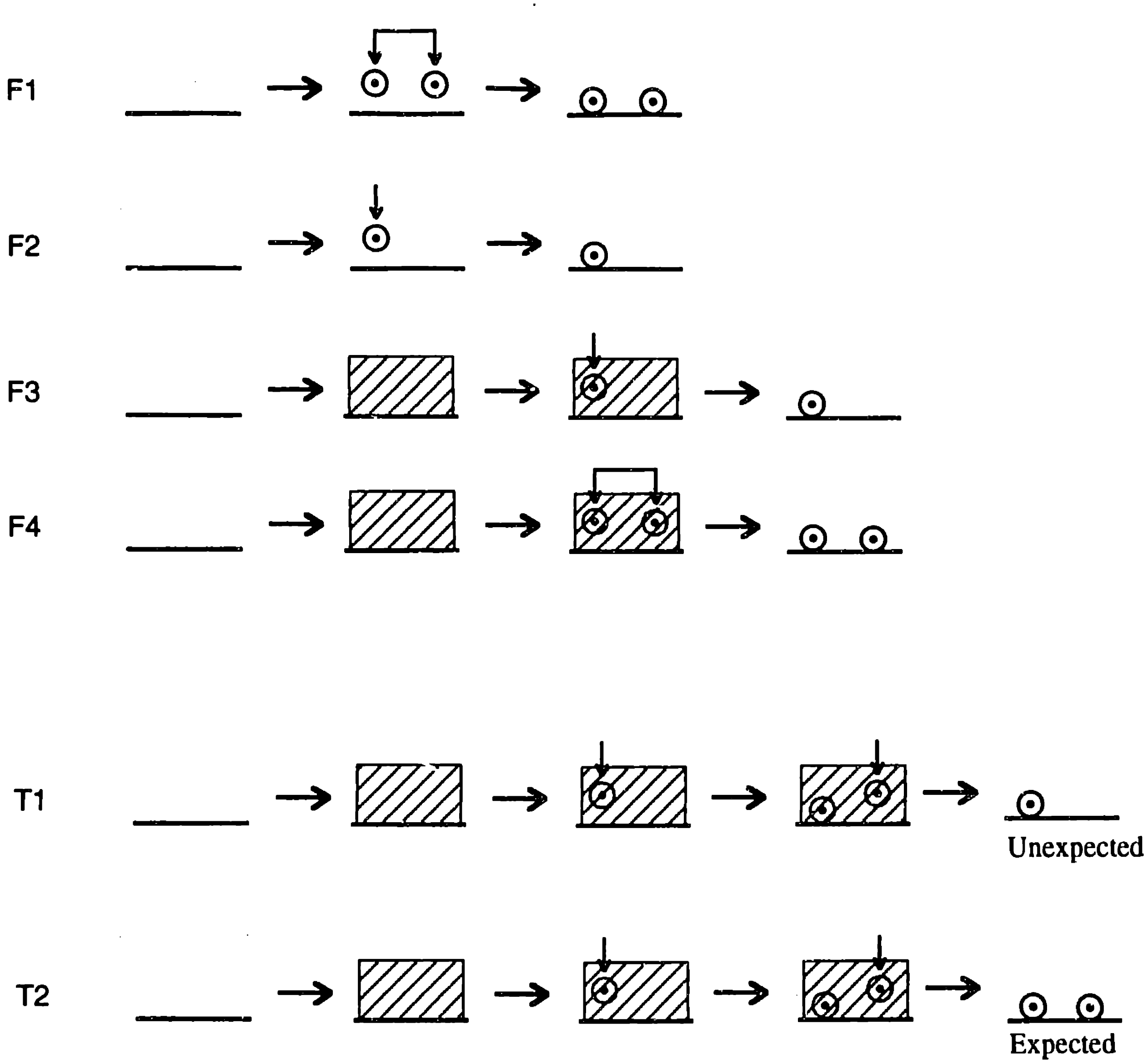


Figure 4

1 + 1 = 2 versus 3

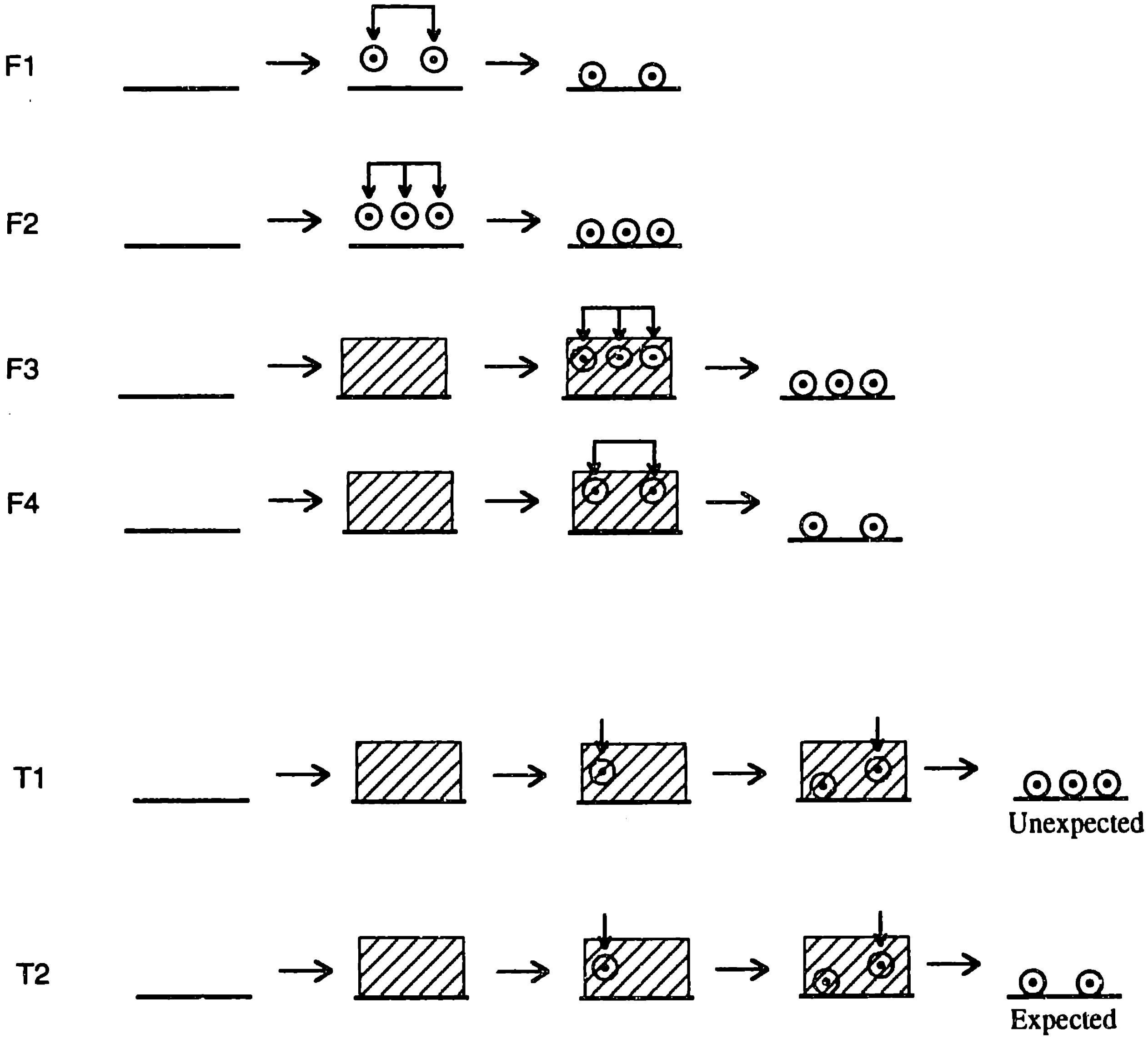


Figure 4

1 + 1 = 2 versus Big 1

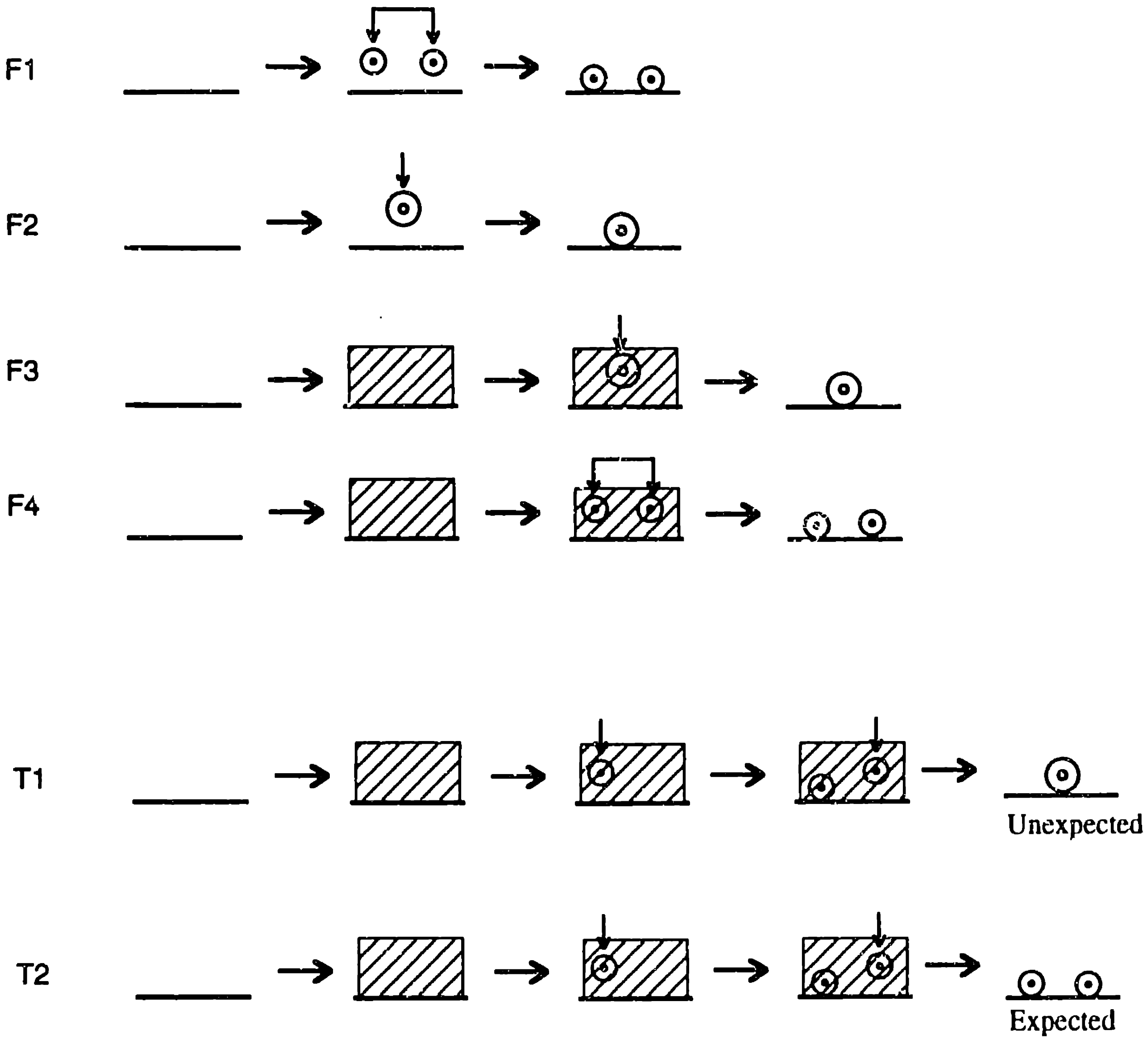


Figure 4

Experimental Stimuli

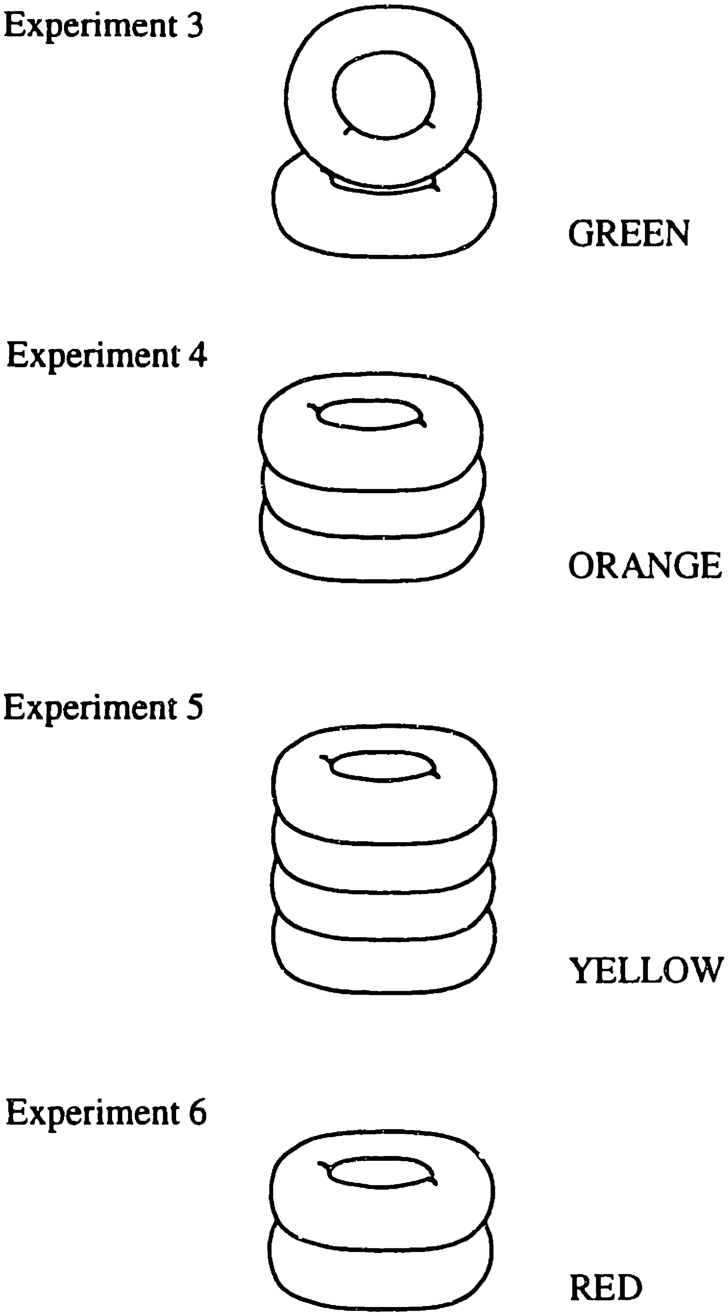


Figure 5

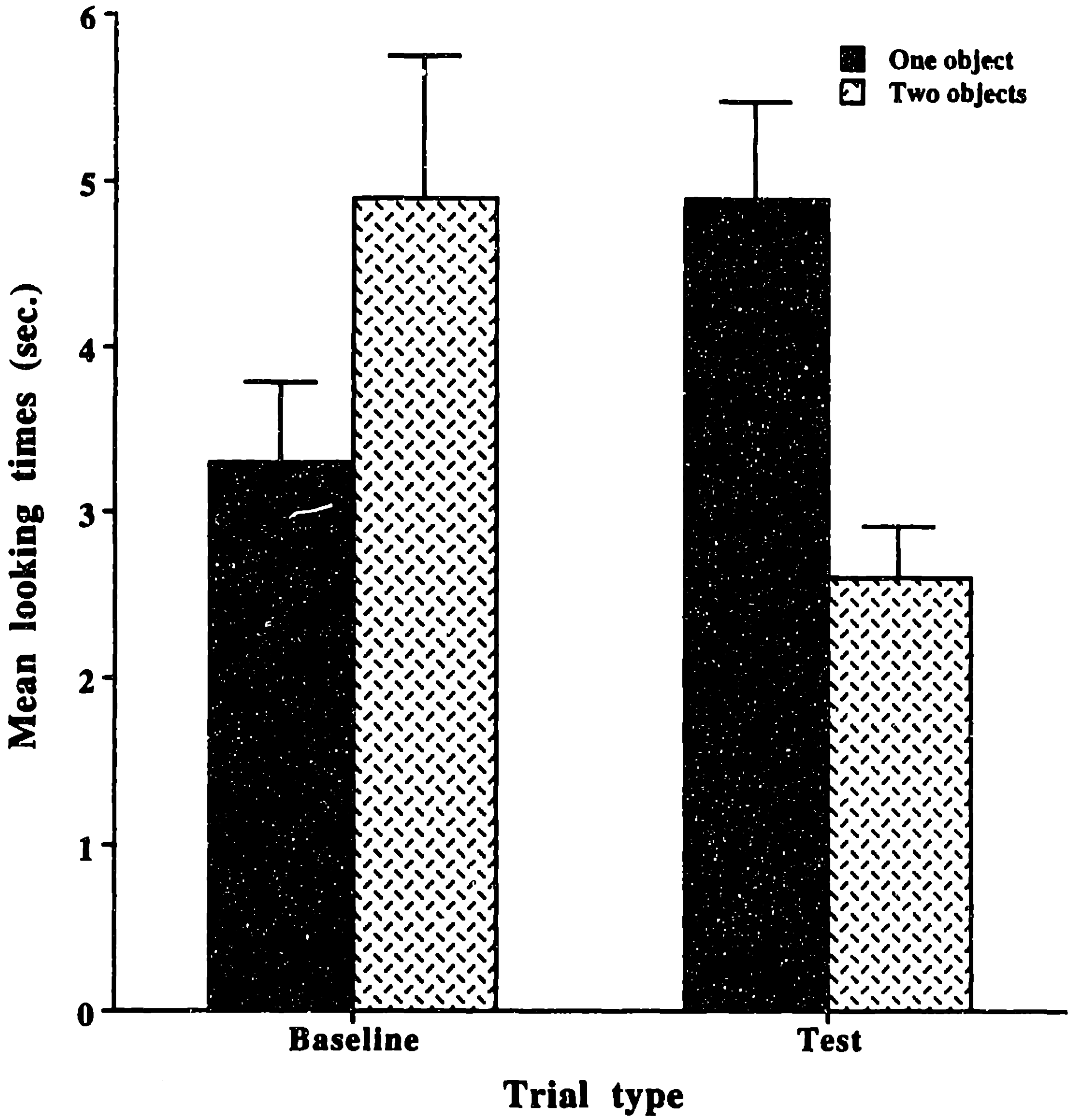
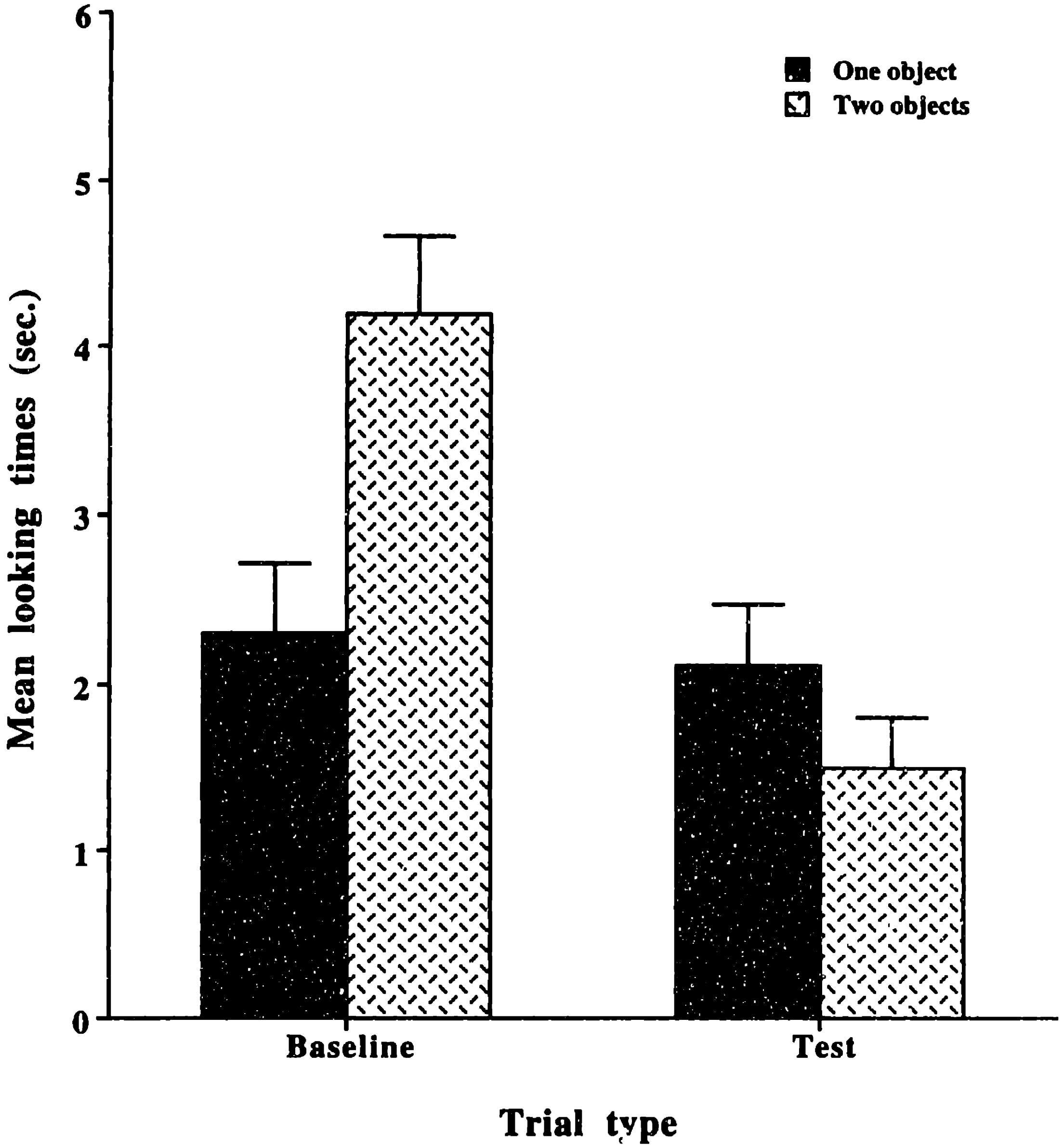
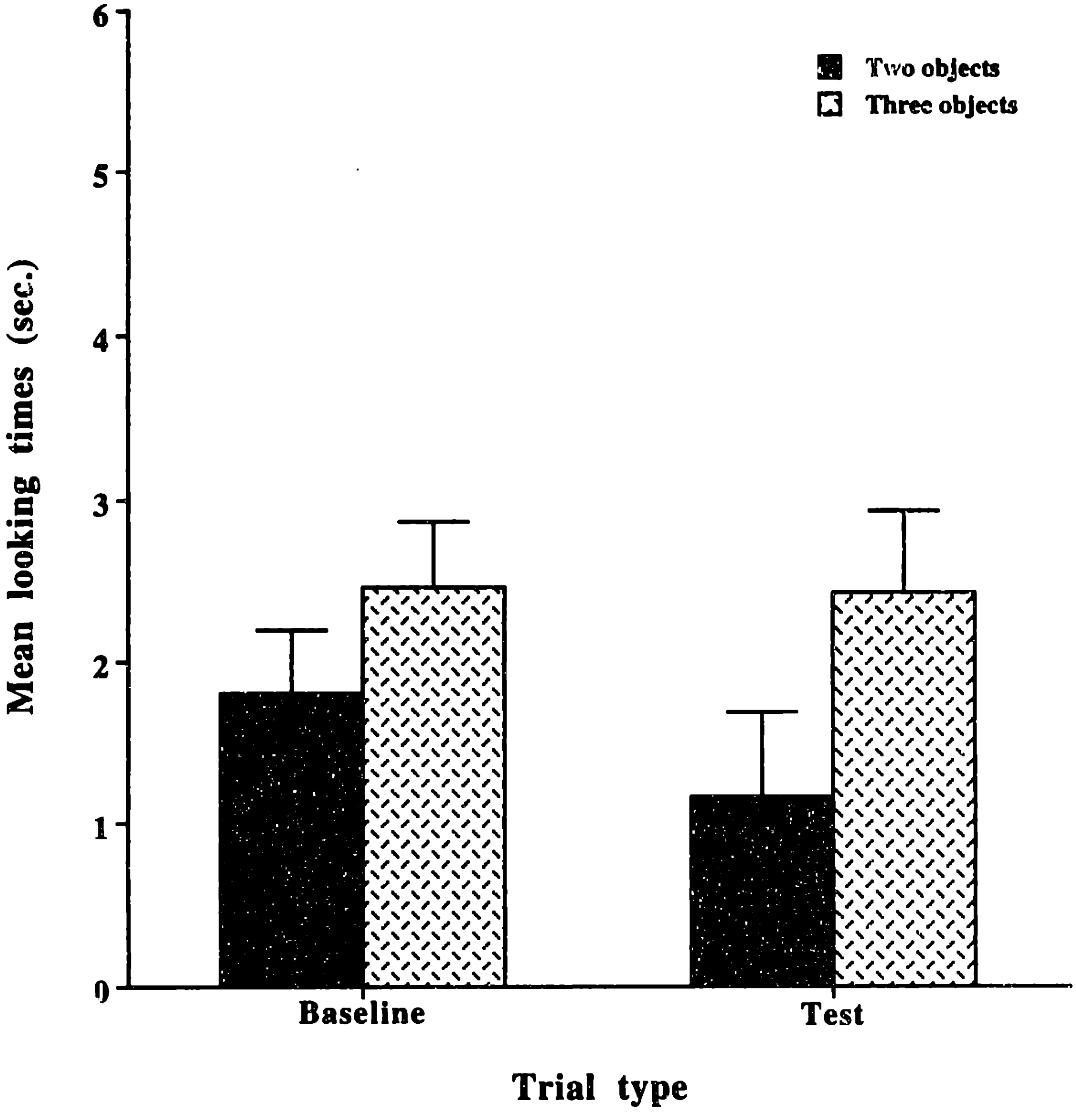

6
5
4
3
2
1
0
Mean looking times (sec.)
■ One object
▨ Two objects
Baseline
Test
Trial type

Figure 6



6
5
4
3
2
1
0
Mean looking times (sec.)
One object
Two objects
Baseline
Test
Trial type

Figure 7



6
5
4
3
2
1
0
Mean looking times (sec.)
Two objects
Three objects
Baseline
Test
Trial type

Figure 8

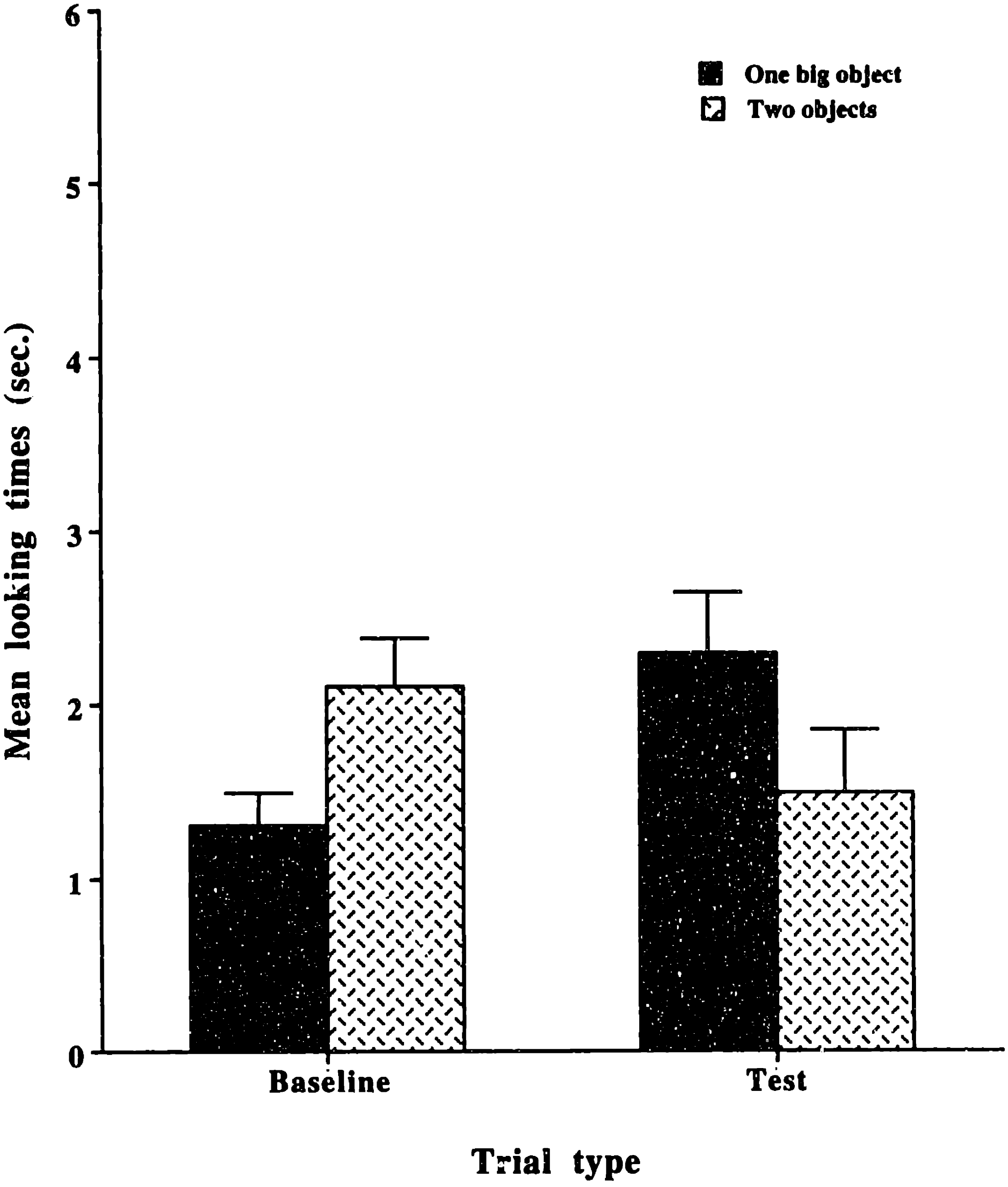

6
5
4
3
2
1
0
Mean looking times (sec.)
One big object
Two objects
Baseline
Test
Trial type

Figure 9

Chapter IV

Is language needed for constructing object kinds? A study with nonhuman primates

Introduction

Since Piaget's (1954) inquiries into the question of how young infants' conceptualize objects in their world and construct the concept of object, developmental researchers have been striving to characterize the infants' understanding of the existence of objects, especially when occluded (Bower, 1974; Baillargeon, Spelke & Wasserman, 1985; Spelke & Kestenbaum, 1986; Spelke, Kestenbaum, Simons, & Wein, 1995; Baillargeon, 1987; Baillargeon & Graber, 1987; Diamond, 1988, 1991; Xu & Carey, 1996). For infants to represent objects they need to start by establishing what an individual object is. They need to individuate objects and trace them through time (trace numerical identity, namely, sameness in the sense of same one). The individuation of objects is the process of determining what individuals are, where one individual ends and another one begins. Thus, for example, at a given moment in time, one may look at an array of two bounded cohesive physical individuals and may parse it as composed of two distinct objects -- the problem of individuation -- and if one sees one individuated object x_i at time A and another identical object at time B, it can be that the second object is x_i or x_j -- the problem of numerical identity. In this respect, the notion is numerical in the sense that there can be two identical objects or there can be only one -- the question is to establish whether an object encountered at time A is the same one as the one encountered at time B.

Criteria for individuation and numerical identity are necessary for object permanence. At least two types of criteria can be used. First, spatiotemporal information provides means for object individuation and for tracing identity over time. This information concerns the spatial and temporal distribution of objects/entities -- for example, one may know that two objects cannot occupy the same space at the same time; one object cannot be at two places at the same time, and objects move from point x_i to point x_y on spatiotemporally continuous paths (Spelke & Kestenbaum, 1986; Spelke, 1988, 1990). Second, property and kind information also allows for the individuation of objects (establish where one object ends and another one begins) and for numerical identity. The use of property cues -- size, shape, color, texture -- may allow one to individuate objects in several cases. One may see a red ball and a blue ball disappear behind a screen and, on the basis of their color, expect two objects to exist behind the screen. However, solely on the basis of properties one cannot always individuate objects. If one desires to count black stuff in a room, one will certainly engage in questioning what kinds of objects are to be counted: chairs, shoes, ...? The conceptual representation of object kinds seems to embody a crucial component for the task of object individuation and object identity.

There is now a body of cognitive developmental research that suggests that young infants establish representations of individual objects and trace their identity through time utilizing both property/kind and spatiotemporal information (Bower, 1974; Spelke & Kestenbaum, 1986; Spelke, Breinlinger, Macomber & Jacobson, 1992; Xu & Carey, 1996).

Spelke and Kestenbaum (1986) investigated whether young infants would individuate objects on the basis of spatiotemporal information. In a habituation paradigm, they presented 4-month-old infants two screens. One object then emerged from the left edge of the left screen, and went back behind the screen. No object appeared in between the screens. Following this emergence, a second identical object emerged from the right edge of the right screen, and went back behind the screen. This sequence was repeated until a criterion of habituation was met. The screens were then removed to reveal either two objects (expected outcome) or one object (unexpected outcome). Four-month-old infants looked longer at the unexpected outcome than at the expected outcome. The researchers proposed that young human infants understood the events as involving two objects because they know that one object moves on spatiotemporally connected paths. If it were the case that one object moved back and forth, it would appear in between the screens. Thus, they analyzed the spatiotemporal discontinuity and inferred that two numerically distinct objects should be behind the screens. However, the question of infants' use of property/kind information was still left open.

Bower (1974) was one of the first researchers to conjecture that spatiotemporal information may be used by infants earlier than they start to use property and kind information to represent distinct individuals. He showed 5-month-old infants objects that disappeared behind screens. For example, an object would go out of sight behind a screen. When it should have reemerged on the other side of the screen, a different object, changed in color, size or/and shape, came out from behind the screen, following the same path and at the same speed as the original object. Bower measured disruption of look at those events, namely, if the infants understood that the object that came out was a numerically distinct object, their looking should be somehow disrupted -- they should look for the original object.

He found that 5-month-old infants changed the looking pattern to these events, and he suggested that this was because the infants realized that the object that emerged from behind the screen was not the same object that disappeared behind the screen. He also found that younger infants did not change the pattern of looking, tracking the emerging object as if it were the object that disappeared behind the screen. Younger infants did not care about the property information provided by the emergence of the second object. On the other hand, when spatiotemporal information was changed, namely, when the path of motion of the same object that disappeared and reappeared from behind the screen was changed, the babies did show evidence of disturbance by looking back to the screen or its edge. He interpreted these data as showing that, before infants use property information to individuate and trace identity of objects, they may use spatiotemporal cues and that it is at age five months that infants begin to rely on property or kind information.

Others have challenged Bower's claims. Replications of his findings were not obtained (Gratch, 1982). Gratch (1982) investigated 5-, 9- and 16-month-old infants' capacity to search for hidden objects. The games the infants played involved people or objects which disappeared and appeared several times from behind a screen. Gratch measured infants' surprise and concern through a coding system for facial expressions and infants' look back to the screen or its edge. Gratch found evidence for disruption in looking, namely, concern or surprise, only in the 16-month-olds, but found no evidence for looking back to the screen because of the changes in property differences between the expected object and the emerging object even among the 16-month olds. Thus, Bower's claims that 5-month-olds expected to see two distinct objects behind the screen could not be replicated even with older infants. Moreover, it may as well be the case that the infants were encoding the differences in properties between the object they saw going behind the screen and the object they saw emerging from behind the screen, without necessarily inferring that there should be two distinct individuals behind the screen. Thus, the babies in these studies may have perceived the changing properties between an object-with-rabbit-properties entering behind the screen and an object-with-ball-properties emerging from behind the screen without setting up representations of each distinct individual.

In order to assess infants' capacity to individuate objects, Xu and Carey (1996) conducted a series of experiments using a methodology adapted from Spelke and Kestenbaum (1986) in which they required the infants to tell how many objects exist behind a screen, namely, the babies saw one object and then another object behind the screen; upon removal of the screen, the babies saw the two objects they had previously seen or only one object. They developed a series of tasks in which they investigated 10- and 12-month-old infants' abilities to individuate objects using conditions where property/kind or spatiotemporal information was needed for object individuation. Ten-month-old infants were presented one of three conditions, a baseline condition, a property/kind condition and a spatiotemporal condition. The baseline condition was devised to show whether there was any intrinsic preference for one-object outcomes or two-object outcomes. The property/kind condition tested the infants' capacity to represent individual objects with the use of property/kind information. The spatiotemporal condition tested the infants' capacity to use spatiotemporal information.

All three conditions started with introductory trials. The babies were shown four trials in which they saw that there were objects (a cup and a toy camel) behind the screen, sometimes one object, sometimes two objects. In the property/kind condition, the infants were then given as familiarization trials a set of four emergences of each of two new toys (a ball and a toy duck). Specifically, one object emerged from behind a screen on one side and then returned behind the screen. A second object then emerged on the other side and then returned behind the screen (i.e. only one object was seen at a time). The objects were never seen co-existing at the same time. The screen was then removed to reveal one object (unexpected outcome) or two objects (expected outcome). After this first test trial, two other emergences of the objects took place, after which the second test trial followed. The whole procedure was then repeated with a second pair of toys (a toy truck and a toy elephant).

In the familiarization trials of the spatiotemporal condition, infants were presented with the same set of four emergences of each toy as for the property/kind condition, except that, on the last two emergences, the two objects were brought out from behind the screen simultaneously, providing spatiotemporal evidence that two numerically distinct objects existed at the same time. The screen was then removed to reveal either one object (unexpected event) or two objects (expected event). The whole procedure was repeated with a second pair of toys (a toy truck and a toy elephant) as in the property/kind condition.

In the baseline condition, the infants were simply shown the outcomes of the experimental conditions without any familiarizations, namely, the screen was removed to reveal one-object outcomes or two-object outcomes.

Xu and Carey found that: (1) In the property/kind condition, 10-month-old infants did not look longer at the unexpected outcome of one object than the expected outcome of two objects, but 12-month olds did. This suggests that infants younger than 1 year of age were unable to use the property/kind differences to determine that more than one object existed behind the screen; (2) 10- and 12-month-old infants did look longer at the unexpected outcome of one object in the spatiotemporal condition, suggesting that they are able to use spatiotemporal information to individuate objects and determine that two distinct individuals existed behind the screen. Moreover, Xu and Carey (1996) found a correlation between 12-month-olds' comprehension of the words for the familiar objects used in the experiments and their success in individuating these objects in the property/kind condition.

Xu and Carey (1996) examined the data from 10- and 12-month-olds in the experiments and the parental reports on the infants' comprehension of the words for the objects used in the task -- ball, bottle, cup, book. They contrasted the data from these two age groups and found that over half of the 10-month-olds were reported not to comprehend those words, whereas 85% of the 12-month-olds were reported to understand at least 2 of those words. Thus, there seems to be a relationship between the capacity to individuate objects in the property/kind condition and the comprehension of the first words, such as "cup", "bottle", "ball", "book".

A stronger test of this relationship derives from a within-age comparison. Analyses were performed on the data of 10-month-olds in the property/kind condition as a function of the number of words comprehended. Xu and Carey (1996) indeed found that the 10-month-old infants who comprehended more than 2 words performed in the property/kind condition as well as the 10-month-olds who were presented the spatiotemporal condition or the 12-month-olds in both conditions. However, the 10-month-olds who understood no words or only one did not succeed in the property/kind condition. Thus, Xu and Carey (1996) found that comprehension of the first words predicted success at individuating objects using property/kind information. It seems that the infants used object kind information, a cup and a bottle, to represent the two objects behind the screen because, in order to comprehend the words for such familiar objects, the infants must have the concepts of the kinds of objects that these words refer to.

At least two different hypotheses can be formulated to address the question of object kind construction being dependent upon the uniquely human linguistic capacity.

Hypothesis 1: The capacity to represent object kinds onto which count nouns map may be part of the human species-specific linguistic capacity. Therefore, the notion of object kinds would be distinctively human.

Hypothesis 2: The capacity to represent object kinds may be part of an evolutionarily ancient adaptation, which predates the emergence of human linguistic representational capacity. Therefore, the notion of object kinds would not be distinctively human.

Different predictions concerning the use of either of these abilities can be drawn from the aforementioned hypotheses. If, on the one hand, nonlinguistic creatures set up representations of distinct individuals on the basis of kind information, thus establishing object kinds, then hypothesis 2 is plausible. It cannot be the case that these creatures are utilizing a linguistic system to represent object kinds simply because they lack one. If, on the other hand, nonlinguistic creatures do not succeed in individuating objects on the basis of kind information, then hypothesis 1 is plausible, namely, these nonlinguistic creatures might need a linguistic system to express object kind concepts.

Thus, to test these hypotheses, we conducted a study based on Xu and Carey (1996) with non-human primates, who obviously lack a linguistic system like our own, to see whether they represent object kind concepts in the absence of language or whether they need a linguistic system to construct object kinds.

First it is necessary to verify whether there is already data that bears on the question of the existence of the object concept in nonhuman primates. A review of the evidence for the representations of this concept by nonhuman primates is presented.

Studies with nonhuman primates on the object concept

There is a vast amount of evidence for the capacity of nonhuman primates to represent objects, mainly from studies on the Piagetian view of object permanence (Blois & Novak, 1994; Diamond, 1988, 1991; Dumas & Brunet, 1995; Mathieu, Bouchard, Granger & Herscovitch, 1976; Natale, Antinucci, Spinozzi & Poti, 1986; Redshaw, 1978; Vaughter, Smotherman & Ordy, 1972; Wise, Wise & Zimmerman, 1974; Wood, Moriarty, Gardner & Gardner, 1980; see also Antinucci, 1989, for a compilation of studies on Piagetian stages in nonhuman primates). Most of this research is concerned with the representational capabilities of nonhuman primates with regards to their capacity to search for hidden objects.

There are at least two types of tasks. One type corresponds to the basic object retrieval task, in which objects are placed into a container; the container is then covered and the monkey is allowed to search for the object (Blois & Novak, 1994; Diamond, 1991; Vaughter, Smotherman & Ordy, 1972). A second type involves what has been commonly called invisible displacement task, in which an object is placed into a container (or hand of experimenter); the container is displaced onto different locations and the object is invisibly placed in one of the muitiple locations, usually the last one visited (Dumas & Brunet, 1994; Mathieu, Bouchard, Granger & Herscovitch, 1976; Wise, Wise & Zimmermann, 1974). In each of these types of Piagetian tasks, it has repeatedly been found that monkeys and apes seem to follow along the developmental sequence suggested by Piaget for human infants.

However, differently from the tasks devised for human infants, this research with nonhuman primates can be characterized by the high level of training that such tasks demand. For example, in order to shape the animal to understand what is required in the task, researchers overload the animals with an immense number of trials, requiring the animals to learn to gaze follow objects, to search for the right object/right location or to place objects in certain location (see Blois & Novak, 1994 for a discussion on the topic). Thus, although most of these studies do not utilize training in test trials, pre-test training sessions are required so that the apes/monkeys learn what the task demands are (Dumas & Brunet, 1994; Mathieu et al., 1976; Wise et al., 1974). It is possible that the training interferes with the animals' performance in the object permanence task. The fact that the animals undergo series of pre-test trials leaves open the question of whether the monkeys have object permanence per se or whether they learn where the object was supposed to be in the course of the experimental trials through either the use of rules -- search at the last location where the experimenter was -- or discriminative stimulus -- the location where the experimenter was (Blois & Novak, 1994).

As far as nonhuman primates' capacity for object individuation is concerned, at least one important piece of evidence can be provided that suggest that such creatures do have spontaneous capacities to individuate objects. As shown in Chapter III, at least two different species of nonhuman primates, rhesus macaques and cotton-top tamarins, are able to represent objects without any training. When confronted with two objects being placed into a box, one at a time, monkeys understood that one object added to another identical object behind a screen yields two objects by looking longer at the unexpected outcome than at the expected outcome. These representations are thus spontaneously available to them. Moreover, these results show that the monkeys set up representations of two objects on the basis of spatiotemporal information. Given that the objects are identical, there is no property or kind information to be used to individuate the objects.

Two innovative studies on nonhuman primates' capacity for object individuation were conducted by Tinkelpaugh (1928, 1932). Tinkelpaugh was interested in the capacity of nonhuman primates to represent hidden objects. In one study (1928), three rhesus monkeys (*Macaca mulatta*) and one cynomolgus monkey (*Macaca fascicularis*) were tested in individual sessions of object individuation in delayed-response tasks. In a series of experiments, he showed the monkeys objects being placed underneath two containers (two tin drinking cups) behind a huge screen. The monkeys sat in front of the screen and could see the experimenter placing food items in one of the two cans behind the screen. Delays as long as overnight period were imposed to test for the monkeys ability to remember where the objects were placed.

One experiment is particularly relevant for the present studies. Tinkelpaugh showed one monkey a piece of lettuce and placed it underneath one of the cups, behind the screen. When the experimenter signaled to the monkey to go get the food, the monkey rushed to the proper cup, picked it up, grabbed the lettuce and rushed away with the lettuce in her mouth. The monkey did not pay any attention to the other cup. The time between the command and the rushing away with lettuce was 3 seconds. Tinkelpaugh then changed the procedure slightly. He showed the monkey a banana, placed it underneath the cup behind the screen. However, surreptitiously, he changed the banana for a piece of lettuce. He then signaled for the monkey to go get the banana, and what happened was completely different from the first trial. The monkey rushed to the proper cup, picked it up, reached for the object, and saw lettuce. She looked around, looked under the cup, in the cup, around the cup, and around herself. She glanced towards the other cup and looked back of the screen. Tinkelpaugh observed that she walked away leaving the lettuce untouched on the floor. The total time between command and walking away was 33 seconds.

This is compelling evidence that the monkey searched for the banana because the monkey had set representations of the objects as being different from each other. When the monkey went to look for the banana and found lettuce, she had set an expectation to find a banana there, she differentiated between the two objects. That she took 33 seconds looking for the banana is evidence for that. However, what Tinkelpaugh did not expect was that the monkey would treat the two objects differently. In a control where he hid lettuce and the monkey found banana, the monkey did not care at all about the identity disparity and happily ate the banana. This asymmetry in object preference -- monkey looked for banana, found lettuce, was "surprised"; monkey looked for lettuce, found banana, was not "surprised" -- contributed to the non-conclusiveness of Tinkelpaugh's results.

Tinkelpaugh's results are highly suggestive that the monkey used property information to individuate the object-with-banana-properties and the object-with-lettuce-properties. Evidence for this is the fact that she differentiated the two objects. The fact that she did not care about the piece of lettuce when she found banana may reflect disinterest interfering with the task: banana may be highly interesting for the monkey, whereas piece of lettuce may be rather dull. Thus, the failure to further search for piece of lettuce might simply mean that, although its properties did not accord with the properties of the object found, the monkey was more interested in eating the banana than looking for the lettuce, due to asymmetrical relevance of the objects to the monkey.

There are at least two other problems with Tinkelpaugh's study. The first one is the anecdotal tone of the study. There were individual observations repeated 15 times in weekly intervals -- that is, the monkey was presented the banana - lettuce event only once. A week later, the monkey was presented the banana -lettuce event again; and so on, for fifteen times, after which the experimenter reversed the order of objects, lettuce - banana for a few weeks. There is no explicit analysis to evaluate the performance of the animal in the task. Moreover, the fact that these studies were conducted with only one or two animals leaves open the issue of how generalizable results with one or two animals are. The use of a very limited number of subjects may entail constraints on broader characterizations of nonhuman primates' cognitive capacities. Although results with single animals are interesting in themselves, showing that these capacities can be found within the genetically constrained representational capacities of such species, it is always a possibility that the results of these tasks may not reflect abilities that can be generalized to an entire population (Boysen, 1994).

The results from Tinkelpaugh's study may embody preliminary data to bear on the question of object individuation with nonhuman primates. However, the asymmetry in salience between the two objects used does not allow for the conclusion that nonhuman primates individuate objects on the basis of kind information. Moreover, just as in the case of Bower (1974) with human infants, only one object was hidden behind the screen. A more sensitive measure than the ones utilized by Tinkelpaugh (1928) or Bower (1974) is needed to test whether the monkeys use spatiotemporal information or property/kind information to track the number of objects placed behind the screen. In Xu and Carey (1996), the infants were required to use property/kind or spatiotemporal information to tell the number of objects. The improvement of this methodology lies in the fact that the subjects are required to tell how many objects exist behind the screen. They see distinct objects emerging from different sides of a screen, after which the screen is removed to reveal two objects (expected event for a human adult) or one object (unexpected event for a human adult). The logic, applied to the nonhuman primate subjects, is that, if they represent objects on the basis of property/kind information, they should look longer at the arrays with only one object than at the arrays with two objects.

The current study

The present research sought to adopt the methodology used by Xu and Carey (1996) to perform an individuation study with a semi-free-ranging population of rhesus macaques. Our main goal was to determine whether they rely primarily on spatiotemporal cues in individuating objects, or if they possess the ability to individuate objects using property/kind information. Several previous studies have successfully replicated other human infant preferential looking and violation of expectancy experiments on nonhuman primate populations. These studies have already established that the use of this method with nonhuman primate subjects yields interpretable results (Rhesus: Hauser, MacNeilage & Ware, 1996; Cotton-top tamarins: Chapter III).

As mentioned before, Xu and Carey (1996) have shown that (1) Property/kind information does not seem to be enough for 10-month-old human infants to succeed in tasks that require them to individuate objects, while spatiotemporal information seems to be crucial for their success in such tasks and that (2) It is not until they are 12 months of age that they succeed in tasks only on the basis of property and kind information alone -- with no spatiotemporal information. Moreover, the correlation found between the infants' capacity to tell objects apart using property/kind information and their knowledge of the corresponding linguistic labels for such objects suggests an intrinsic relationship between object individuation and acquisition of the first words to the familiar objects. One way to test for the hypotheses that relate these capacities present in prelinguistic human infants is to investigate nonlinguistic creatures such as nonhuman primates.

In adapting the infant preferential looking and violation of expectancy methodology for use with the species selected, several changes in the experimental arrangement had to be made. First, a new apparatus needed to be devised and constructed. Given the environmental conditions of the field studies, this was necessary so that the apparatus was small enough to be transported onto the island by boat, light enough to be carried along from 7 am to 5 pm during the days of testing and sturdy enough to resist different sorts of accidents, such as rain, or during transportation on boat or while being carried on the island.

Second, whereas in the infant studies the stimuli are generally toys, here we used edible items because pretesting had determined that the monkeys would be more willing to pay attention if the stimuli looked like food. The stimuli found most appropriate, according to the availability of the local provision, were bright orange carrots and a yellow squash that was cut into slices roughly the same volume as the carrots.

Changes were also made to the experimental design. In Xu and Carey (1996), there were three groups of infants tested in one of three conditions, a baseline, a property/kind and a spatiotemporal condition, in a between-subjects design. In the present study, different groups of monkeys were tested on either one of two test conditions only, a property/kind condition and a spatiotemporal condition. In the property/kind condition, the monkeys saw two non-identical objects come into view, and then disappear behind a screen, one at a time. Specifically, there was temporal discontinuity between the emergences of one object and the other object. In the spatiotemporal condition, the monkeys saw two non-identical objects come into view, both at the same time, and then disappear behind a screen.

Two other differences concerning experimental design regarded 1) the number of introductory and familiarization trials the monkeys were presented and 2) the number of pairs of objects utilized in the test trials. In Xu and Carey, the babies were presented with four introductory trials, four familiarization trials, one test trial, two other familiarizations and a second test trial. After this first phase of test trials, the whole procedure was then repeated with a second pair of toys. This procedure was far too long to test rhesus monkeys in a semi-wild setting. Thus, the whole procedure was shortened to fit the constraints of the experimental situation. Only two pairs of familiarizations and one pair of test trials, with one pair of objects, were used in the present design.

Method

Subjects and Study Environment

Experiments were conducted, during a period of 5 days, on a semi-free-ranging population of rhesus monkeys (*Macaca mulatta*) living on the 15-hectacre island of Cayo Santiago, Puerto Rico (see Rawlins and Kessler, 1987 for a description of the island and history of research on this population). The population consists of approximately 900 individuals, divided roughly into five to six social groups. Cayo Santiago is inhabited only by these monkeys; there are no natural predators. Personnel of the Caribbean Primate Research Center provide food (Purina monkey chow) every morning, distributed across three feeding dispenser corrals on the island. Subjects are extremely well habituated to the presence of human observers and individuals can be easily recognized from unique chest tattoos and ear notches. Maternal kinship, age and sex are available from a long term data base. In this population, females reach adulthood at approximately three years whereas males reach adulthood at approximately four years.

While attempts were made towards testing both males and females, the females tended to be far more easily distracted than the males. Females were generally engaged in social activities such as grooming or/and infant caring, which impeded experimental testing. Not a single female, of the few available for testing, finished an experimental session. Therefore, the data reported below come from adult male subjects.

Subjects were selected based on their age as well as the apparent favorability of experimental conditions at the time (e.g., proximity to other monkeys, orientation of the subject relative to the experimenter, degree of the subject's engagement with other activities). Subjects were tested when they were resting and either alone or in small social groups (1-6 monkeys). When a subject was located, we set up the testing apparatus and the video camera and then proceeded to run the individual experimental sessions.

Data from 48 adult male rhesus monkeys were used in this study. One hundred and three animals were excluded from the study due to aborted or repeated sessions when the animals showed no interest in the proceedings. The most common factor causing distraction was the initiation of social interactions by nearby individuals. Sessions were thus aborted if any of the following occurred: (1) Subjects moved or failed to look steadily towards the stage area at any point during familiarization or test trials for at least 1 s.; (2) The time elapsed between successive trials within a session exceeded 120 seconds.

Materials and Apparatus

The individual sessions were conducted using a white foam core box, measuring about 60 cm x 30 cm x 40 cm. The box had a platform base and a back cover, but no sides. A screen with a hidden tray attached to the back of it covered the front when it was in place. The bottom edge of the screen fit into a groove in the platform base. Figure 1 shows the apparatus and the conditions of testing.

Two objects were used as stimuli: a bright orange carrot, measuring about 22 cm long and 3 cm in diameter in its fattest end, and a slice of bright yellow squash, roughly about 20 cm long (curved) and 2 1/2 cm thick. Both the carrot and the piece of squash were substituted by another identical carrot and another identical piece of squash on the third day of experimentation on the island. The original objects became rotten due to heat, humidity and manipulation.

Insert Figure 1 about here

Design and Procedure

Twenty-four subjects were assigned to each of two conditions: the Property/Kind condition (PK) or the Spatio-Temporal condition (ST). PK and ST were both modeled on Xu and Carey (1996) with four differences. First, there was no between-subjects baseline condition. Second, the number of times the objects emerged from behind the screen was less in both introductory and familiarization trials. Third, the objects used were unfamiliar to the monkeys. Fourth, the pair of objects utilized in all of the test trials was the same.

Each condition consisted of two sections: pre-test familiarization trials and test trials. The pre-test trials served to familiarize the monkeys with the objects and the apparatus. The monkeys learned that there were objects behind the screen. These pre-test trials did not provide any information as to the number of objects that would be present when the screen was removed. The two test trials involved one of the two outcomes, namely, the expected outcome (two objects) or the unexpected outcome (one object).

Property/Kind Condition

Each subject was shown a series of four pre-test familiarization emergences, one test trial, two additional familiarization emergences, and the second test trial. Pre-test and test trials of the property/kind condition are illustrated in Figure 2.

Insert Figure 2 about here

A familiarization trial consisted of the experimenter showing the monkey one object emerging from behind the screen to the left or right of the experimenter, who sat directly behind the testing box, aligned with its center. Once the monkey had looked at the object for at least 2 s, it was brought back behind the screen. Immediately thereafter, the second object was brought out from the other side of the screen. After the monkey had looked at this object for at least 2 s, it was again brought back behind the screen. In the third familiarization trial, the experimenter brought the first object out from behind the side of the screen where she had first brought it out, laid it on the ground, and left it there for the monkey to look at it for approximately 5 s before bringing it back behind the screen. In the fourth familiarization trial, the experimenter brought the second object out from behind the side of the screen where she had previously brought it out, placed it on the ground, and let the monkey look at it for 5 seconds before bringing it back behind the screen.

Immediately following the first four familiarization trials, the first test trial was presented. The screen was lifted up and placed behind the box, revealing either one object (the unexpected event) or two objects (the expected event). To produce the unexpected event, the experimenter placed one of the objects in the hidden tray attached to the back of the screen during the third or fourth familiarization trial. The trial in which this occurred depended on whether the one-object outcome was the last object seen or the one before last seen by the monkey. The subject was allowed to look at the display for a maximum of 10 s, after which the experimenter replaced the screen in front of the box.

After the first test trial, there were two familiarization trials. They consisted of the first and second objects emerging from and returning behind the left and right sides of the screen respectively. These trials were identical to the very first two familiarization trials. In the second test trial, the screen was lifted up again and placed behind the box, revealing either the expected or unexpected event -- the opposite of what the subject saw on the first test trial. After 10 seconds had elapsed, the experimenter replaced the screen in front of the box and announced that the session had ended. The criterion was set on 10 seconds because of previous evidence form other studies utilizing the preferential looking and violation of expectancy measure with nonhuman primates (Chapter III) that suggested that this amount of time covers satisfactorily the lapse of interest of such subjects.

Spatiotemporal Condition

The procedure for this condition was exactly the same as in the property/kind condition. It differed from that one only with respect to the third and fourth familiarization trials. Figure 3 illustrates the pre-test and test trials in the spatiotemporal condition.

Insert Figure 3 about here

In the third familiarization trial, the experimenter brought the first object out from behind the left or right side of the screen, laid it on the ground and, immediately following the emergence of the first object, while this object was on the ground for the monkey to look at it, brought the second object out from behind the right or left side of the screen, laying it on the ground as well, such that now both objects were on the ground, in front of the monkey. The monkey was allowed to look at both objects for approximately 5 s before the objects were brought back behind the screen simultaneously. The procedure then unfolded as described for the property/kind condition.

Subjects were tested when they were resting and either alone or in relatively small social groups, 5 to 10 animals. When a subject was located, we set up the apparatus from a distance of approximately 1.5 - 2 meters between subject and testing box/experimenter and then proceeded to run the individual experimental sessions. One experimenter and two observers were involved in both conditions. While the experimenter presented the stimuli, one observer stood directly behind the experimenter and recorded the session and a second observer stood off to the side (approximately 1 - 1.5 meters away, depending on the terrain) recording observations of the experimental session. Among other things, we also noted the monkey's ID number, apparent attentiveness in all of the trials, any differences in procedure that accidentally occurred, and outside factors that came into play during the course of the experiment. The video camera, testing apparatus and the experimental subject were lined up in a straight line so that the video record provided an unambiguous, head on view of the subjects' eyes. In video taping a trial, we attempted to fill as much of the recorded image with the subject's head as possible.

The start of each familiarization and test trial was announced by the experimenter, for the benefit of the off-line observers as well as of the observer videotaping the session. The experimental sessions were recorded on a video camera model Panasonic IQ404. While the live observers (who later coded the looking times from the videotapes) were aware of which condition was being run during a given session, they later reported that they could not tell from the videotapes which test event (expected or unexpected) was being shown first.

Analog records of the videotapes were digitized onto a Macintosh Quadra 950 using the Radius VideoVision board. Frame-by-frame quantification (30 frames/second) of the total amount of time looking at the display (out of 10 seconds) was then scored using the Adobe Premiere (version 4.2) software. Since approximately 30 frames go by in the space of one second, this mode of analysis is highly accurate and enables the viewer to enforce an extremely strict criterion for when the monkey looks or does not look at the display. Scores of looking times were quantified as the total amount of visual fixation, in frames, out of 10 seconds in the direction of the display.

The observers who coded the videotapes at the Primate Cognitive Neuroscience Laboratory at Harvard University were the live observers who helped run the sessions at Cayo. They separately coded the looking times of all 48 subjects. They were blind to the experimental conditions presented. A correlation analysis on the looking times of the first four monkeys indicated that inter-observer reliability was 99.5%. The following analyses utilized data from the primary observer. The primary observer was assigned according to level of experience in the laboratory as a videotape coder. The following analyses were performed on the looking times as measured in the total number of frames.

Results

Condition (property/kind, spatiotemporal), object (carrot, piece of squash), outcome order (one-object outcome first, two-object outcome first), object in unexpected outcome (last seen prior to test, not last seen prior to test) and side of one-object outcomes (left, right) were between-subjects variables, whereas outcome (one object, two objects) was within-subjects variable.

Preliminary analyses revealed no main effects or interactions involving either object (carrot, piece of squash), or side of one-object outcomes (left, right), or object in unexpected outcome (last seen prior to test, not last seen prior to test). Subsequent analyses were therefore collapsed over these variables.

Figure 4 shows the mean looking times at one and two objects in PK and ST conditions. In the PK condition, 15 out of 24 monkeys looked longer when there was only one object in the box than when there were two objects ($\underline{M}_{\text{one object}}$ = 3.9 s.; $\underline{M}_{\text{two objects}}$ = 2.8 s.). In the ST condition, 21 out of 24 monkeys looked longer at the outcome of one object than at the outcome of two objects ($\underline{M}_{\text{one object}}$ = 3.6 s.; $\underline{M}_{\text{two objects}}$ = 2.5 s.).

Insert Figure 4 about here

A 2 x 2 x 2 ANOVA compared looking times with condition (PK, ST), outcome order (one-object outcome first, two-object outcome first) and outcome (one object, two objects) as variables. There were no main effects of condition or outcome order, although there was a significant interaction between these two variables: ($F(1, 44) = 6.283$, $p < .02$). The monkeys in PK condition had longer looking times when the one-object outcome was the first test trial, whereas in ST condition, the monkeys looked longer when the two-object outcome was the first test trial.

More importantly, there was a main effect of outcome ($F(1, 46) = 21.148$, $p < .0001$). The monkeys looked longer at the unexpected outcome of one object ($\underline{M}_{\text{one object}} = 3.7$ s.) than at the expected outcome of two objects ($\underline{M}_{\text{two objects}} = 2.5$ s.). Moreover, there were no interactions involving this variable.

In order to further test whether there were differences between the two conditions, separate t-tests for each condition alone were performed to compare the pattern of looking times for one and two objects. They revealed a significant difference between looking times at one and two objects for both PK condition ($t\ (23) = 2.803$, $p<.01$, two-tailed) and ST condition ($t\ (23) = 4.375$, $p<.0001$, two-tailed). The monkeys looked significantly longer at the unexpected outcome (one object) than at the expected outcome (two objects) in the property/kind condition and in the spatiotemporal condition.

Further non-parametric analyses (Wilcoxon signed-rank test, corrected for ties) performed on each condition alone revealed that, in PK condition, 15 out of 24 subjects showed a stronger preference for looking at the unexpected outcome of one object than at the expected outcome of two objects (Wilcoxon $Z = -2.18$, $p < .03$), whereas in ST condition, 21 out of 24 subjects showed a stronger preference for looking at the unexpected outcome of one object than at the expected outcome of two objects (Wilcoxon $Z = -3.54$, $p < .0005$). A Mann Whitney U test (corrected for ties) comparing the two conditions revealed no difference between them (Mann Whitney $U = -.206$, n.s.).

General Discussion

The main results of this study are the monkeys' successes in both PK and ST conditions. They looked longer at the unexpected outcome of one object than at the expected outcome of two objects in both conditions. Taken together, these data show that the monkeys were sensitive to the presence of two distinct objects behind the screen and succeeded in using property/kind information alone to individuate the objects and set up expectations about the number of objects to be behind the screen. The evidence provided by the present results is consistent with the possibility that the monkeys use property/kind differences between objects to individuate them.

The present findings show that nonhuman primates spontaneously represent objects. The possibility of investigating spontaneous cognitive abilities of nonlinguistic creatures, such as rhesus macaques, was proven successful with the use of the preferential looking and violation of expectancy method. Spontaneous representations such as the ones researched here, in general, are not assessed in methods that utilize training (Blois & Novak, 1994). The rhesus monkeys set up spontaneous representations of distinct objects without any training. These results also demonstrate that the monkeys represented distinct objects under unconstrained field conditions. Unlike a laboratory situation, where control of the experimental setting can be fulfilled, the experimental situation of this study was uncontrolled in that the monkeys were free to do whatever they wanted. Interactions with other animals and natural disinterest in the task interrupted experimental sessions.

These results further confirm the findings that nonhuman primates have object permanence (Antinucci, 1989). Rhesus monkeys, as also in the case of Tinkelpaugh's (1928) cyno monkey, establish representations of distinct individuals. They individuate objects and understand the object concept because they set up representations of two hidden objects -- namely, they looked longer when there was only one object revealed upon removal of the screen. They use spatiotemporal and property/kind criteria for the individuation of such objects. Primarily, the results suggest that the monkeys believe that objects do not cease to exist when they are occluded from view. The results also show that the monkeys established individuals in the first place. In the present study, the objects were hidden behind the screen all the time. They never saw the experimenter put the objects behind the screen. They used the information provided by the emergences of each object -- both property/kind and spatiotemporal -- to infer that two distinct individuals existed behind the screen.

The data from the present study, however, do not provide evidence for object individuation using spatiotemporal information alone. In the spatiotemporal condition, the monkeys have available both property/kind information and spatiotemporal information. The fact that the objects were different in kind and in properties provided extra information to the spatiotemporal condition. In the number experiments (with human infants, as reviewed in Chapter I; with nonhuman primates: Chapter III here, Hauser et al., 1996; Uller, Carey & Hauser, 1996), the objects are generally identical, and the lack of property/kind information requires the subjects to use spatiotemporal information only for the individuation of the objects. These number studies provide evidence for monkeys' use of spatiotemporal information alone to tell the number of objects to be found behind the screen. Contrary to the present study, in Chapter III, the monkeys used spatiotemporal information to individuate the objects, given that there were no property/kind differences between the objects involved in the addition and subtraction studies.

It should be noted that this was not an exact replication of Xu and Carey (1996) and that some of these differences may have affected the results. For example, it is possible that the monkeys succeeded in these experiments because of the motivational significance of the experimental objects used. Food objects were intentionally utilized with the monkeys in order to stimulate maximal possible interest, but may have affected their attention differently than the non-food objects used on the infants (toys, familiar objects). Although these food items may be highly interesting for these monkeys, the objects utilized in the infant studies may have been highly interesting as well. They were the most familiar objects (toy duck, ball, book, bottle) babies usually see in their environment, being highly significant for them (bottle, cup, toys). In the present study, we believe that the piece of squash and the carrot were completely unfamiliar to the monkeys. Not only were the monkeys not familiarized with the objects in the course of the experimental session, but had never seen them prior to this experiment.

Important differences between the design of the present study and the design of the infant studies were: (1) fewer emergences of the objects both in the pre-test phase and in the test phase; (2) fewer number of pre-test and test trials and (3) objects were presented for shorter periods of time than in the infant studies, due to the constraints of the field environment. All of these differences should have made it harder for the monkeys to succeed in individuating the objects. The monkeys succeeded in these tasks despite these differences. However, a fourth difference may have implications for these results. Specifically, the monkeys were not tested on a baseline condition to measure preferences for looking at one and two objects. It may be argued that the monkeys could have looked longer at one object in both PK and ST conditions because they naturally have an intrinsic preference for one object over two objects. However, this is not the case in either the infant number studies (Chapter II), the infant individuation studies (Xu & Carey, 1996) or the nonhuman primates' number studies (Chapter III here, Hauser et al., 1996). Therefore, it is highly unlikely that the monkeys in the present studies would have this preference for one-object displays.

There were no statistically significant differences in looking times between the carrot and the piece of squash. These two objects presented the same level of salience in that the monkeys presented roughly the same amount of looking times to the carrot and the piece of squash. This is important because, in Tinkelpaugh's (1928) experiments, there was a significant relationship between the level of salience between the food-objects and the monkey's capacity to individuate the objects. The monkey only showed a disruptive behavior (long searching times) when she saw lettuce instead of banana -- that is, the experimenter had hidden banana and she found lettuce. When the experimenter hid lettuce and she found banana, she did not care and happily ate the banana without spending time to look for the lettuce. In the present experiments, rhesus monkeys looked equally long at the carrot and at the piece of squash in the one-object outcomes, showing that they did not prefer one object over the other.

Note also that, and in contrast to Tinkelpaugh (1928), who used one female monkey in the banana/piece of lettuce study, the present experiment investigated the capacity to individuate objects in a population of rhesus macaques. Boysen (1994), among others, has suggested that individual differences between primates exist. The fact that an ability can be shown in one or two subjects may imply that the capacity constitutes part of the genetic endowment of the particular species. However, it does not necessarily entail that a generalization of the same capacity to an entire population of that species can be drawn.

One might argue that the strength of these results may be minimized to a large extent by the difficulties in retaining subject attention over the course of the entire experiment. As indicated, the vast majority of the individuals tested (There were 103 aborted sessions out of 151 tested monkeys = approximately 68%) stopped looking at some point of the experimental session, which then had to be aborted. Roughly the same success rate was obtained in Part I of Chapter III, namely, about 62% of the subjects were lost due to inattention. In the present study, 48 subjects were shown to be successful in paying attention to all experimental trials, and it is rather striking that the monkeys were able to succeed in individuating the objects in the complex and distracting setting of their natural environment. Social distractions are rather frequent. Moreover, the experimental sessions of this study were much longer than the trials of the number studies performed on the same population (Hauser et al., 1996; Part I of Chapter III). Therefore, success rate in this study seems actually higher than expected.

The data presented here show no evidence for the hypothesis that the capacity to represent object kinds is part of the human species-specific linguistic capacity. At least, the experiments are consistent with the hypothesis that nonhuman primates represent object kinds in the absence of a linguistic system. The ability to individuate the objects on the basis of spatiotemporal and property/kind information is genuinely spontaneously present in rhesus macaques, contrary to the prediction that the language faculty would be driving the construction of object kinds. It is possible that the notion of object kinds is not distinctively human, and thus may be part of an evolutionarily ancient adaptation that predates the emergence of human linguistic capacity. If the notion of object kinds is not inherently human, then why is there a correlation between infants' understanding of the words and object individuation by kind?

One can speculate that the correlation between word comprehension and the establishment of objects kinds found by Xu and Carey (1996) bears replication. As these investigators pointed out, the study was not devised to specifically address this question. The aim of that study was to investigate human infants' ability to use different sorts of information to individuate objects. However, if this correlation holds, namely, if a relationship between object kind individuation and comprehension of words is indeed found, it may be that the language faculty of human infants provides the environment for them to expect that words refer to kinds, that words map onto kinds.

Maturational changes may also play a role in the construction of object kinds. Research in the object permanence field (Diamond, 1991; Redshaw, 1978; Vaughter, Smotherman & Ordy, 1972) shows that human infants and nonhuman primates undergo parallel maturational development. The most important piece of evidence that the cognitive development observed in young human infants is comparable to the development of young rhesus infants comes from data of object retrieval tasks (Diamond, 1991). Diamond required human infants and rhesus infants to reach for an object placed inside a transparent box. Infant monkeys of 1 1/2 months performed much like human infants of 7 1/2-8 months -- they reached through the side of the box they were looking. By 4 months, infant monkeys are perfect on the object retrieval task, just as are 12-month-old human infants. It is possible that human infants' cognitive capacities develop between ages 10 and 12 months such that the acquisition of object kinds parallels language acquisition.

Alternatively, there is also a possibility that the monkeys individuated the objects on the basis of object-with-carrot-properties and object-with-piece-of-squash-properties, not necessarily on the basis of the kind information (carrot and piece-of-squash). In the property/kind condition, the monkeys may be using the differences between something being orange and shiny (carrot properties) versus yellow and dull (piece of squash properties) to realize that there are two objects behind the screen. If the monkeys do not represent object kinds, then there may be something specific about humans. Perhaps the difference between the human infants and the rhesus monkeys in that human infants are, by virtue of being humans, <u>prelinguistic</u>, whereas primates do not possess a language faculty. It is possible that, for reasons unknown, infants before age 12 months do not attend to object kinds. They individuate objects by primarily tracking them through time and perhaps on the basis of general gross properties. Once infants start conceptualizing entities as kinds of objects, primarily on the basis of shape, and learn to understand that count nouns refer to such kinds of objects, then the mapping is established. Nonhuman primates, on the other hand, may conceptualize objects on the basis of shape alone, from the start to the end. Given that they lack language, it is a logical possibility that they will never need object kinds to represent objects in their world and simply lack this capacity.

As it is possible that infants represented the objects on the basis of information such as shape -- cup-shape, bottle-shape, what is the relevance of shape in object kind construction? Shape is a special type of property in that it marks kind of objects. It is not as salient as color or texture. Human adults, for example, if presented in a situation where a red ball goes behind a screen and then a green ball goes behind the screen, will expect two distinct individuals, one red, one green, to be behind the screen. Adults can individuate objects on the basis of color alone. Human infants, on the other hand, prioritize shape over color. When presented with a similar situation, infants will individuate objects when shape is different, and will individuate on the basis of color only on certain constrained conditions (Leslie, Hall & Tremoulet, 1996). Given that shape is a predictor of kinds, it is possible that the correlation between object kinds and word comprehension reflects the fact that the infants are starting to attend to shape on their way to object kind construction.

These alternatives still leave open the question of whether the monkeys' use kind information to individuate distinct objects. It may be the case that monkeys use properties to individuate the objects, and certain properties are more salient (such as shape) than others. As suggested, the infants seem to use shape information before they use color or texture, which implies that shape may be guiding the infant developing language comprehension capacity since shape marks object kinds. A possibility is that nonhuman primates individuate objects irrespective of properties. For example, it is possible that the monkeys will be able to individuate a red carrot and a yellow carrot as well as human adults would. The question is not whether monkeys represent object properties because there is evidence they do from the property/kind condition. It may be that a property such as shape, salient to human infants, is not as salient to monkeys. Further tests are needed to find out what kinds of properties, and to what degree, nonhuman primates use for individuating objects.

These results are intriguing and strongly suggest that, whatever the relationship is between the acquisition of object kind concepts and the development of language comprehension, it is very possible that the linguistic faculty is not specifically responsible for the development of property/kind individuation in human infants.

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Figure Captions

Figure 1. Schematic drawings of testing conditions for the experimental sessions.

Figure 2. Schematic drawings of familiarization and trials for the property/kind condition.

Figure 3. Schematic drawings of familiarization and trials for the spatiotemporal condition.

Figure 4. Mean looking times for one and two objects in the test trials of the PK and the ST conditions.

Experimental conditions of the study in Cayo Santiago, Puerto Rico

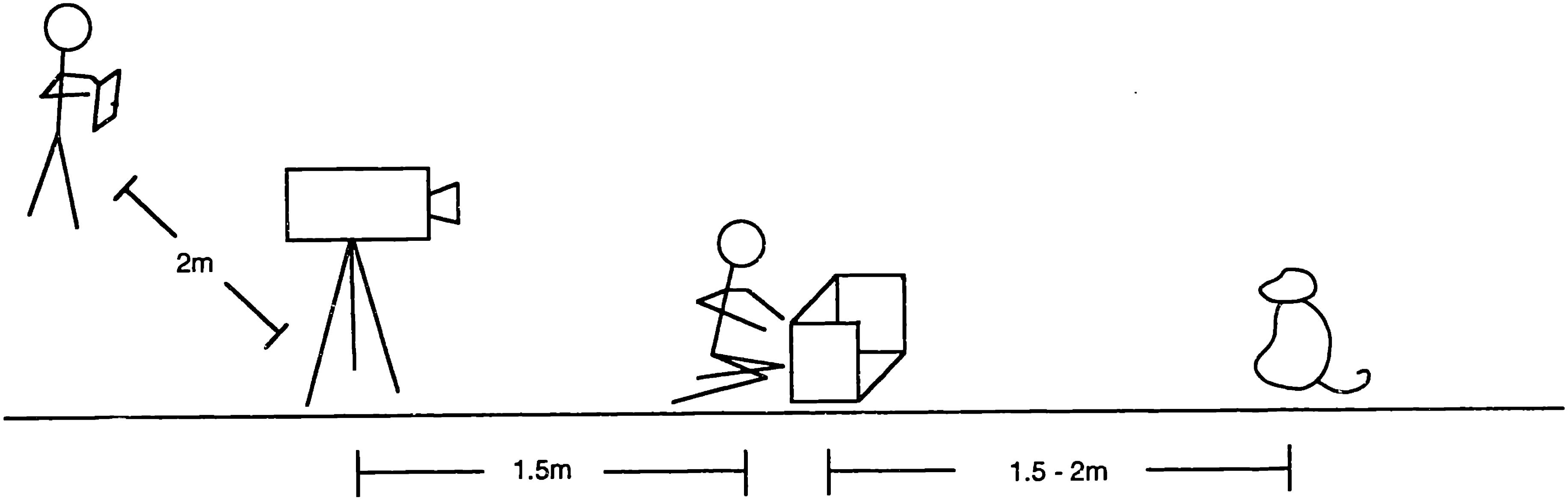
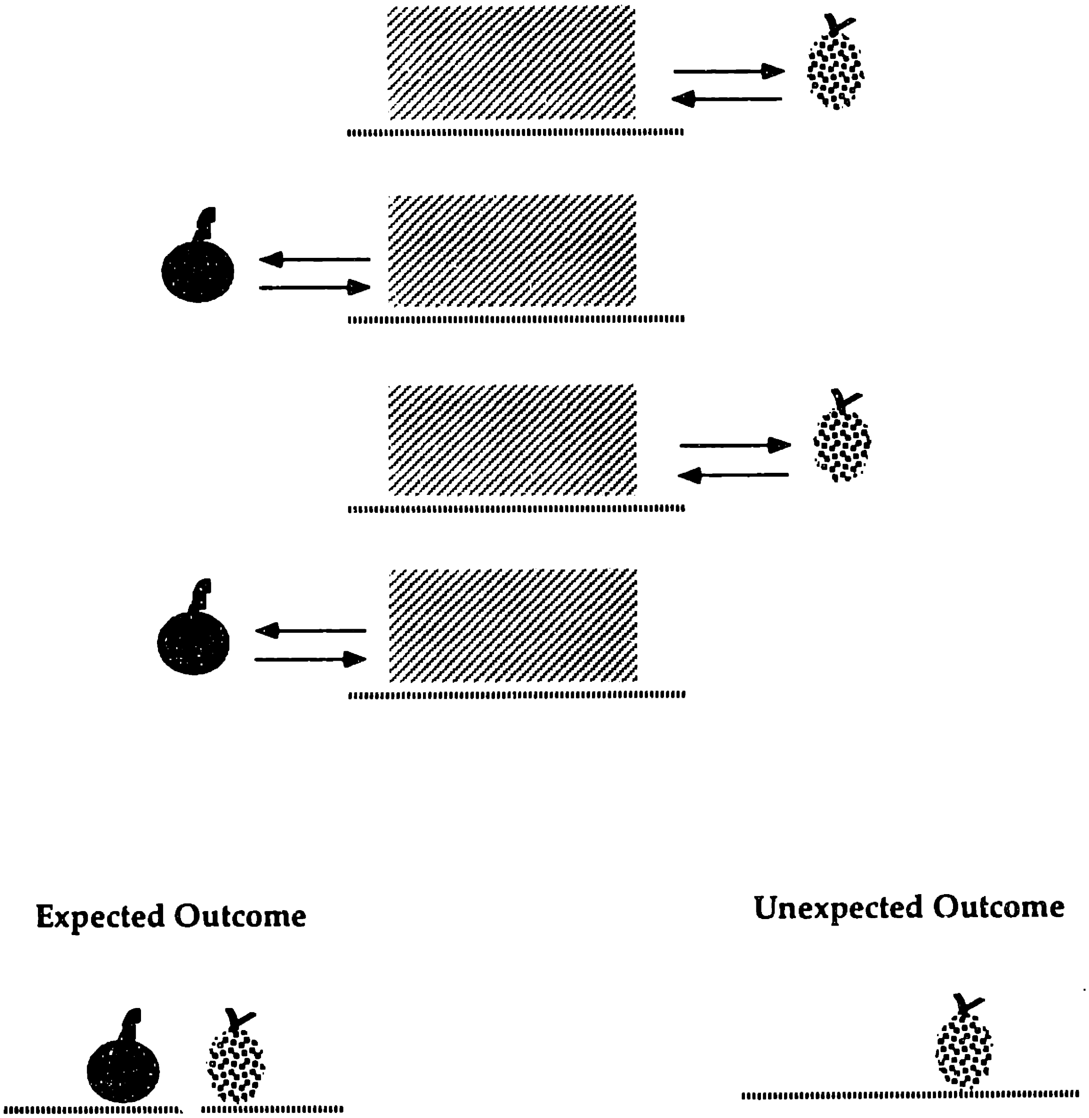


Figure 1



Expected Outcome

Unexpected Outcome

Figure 2

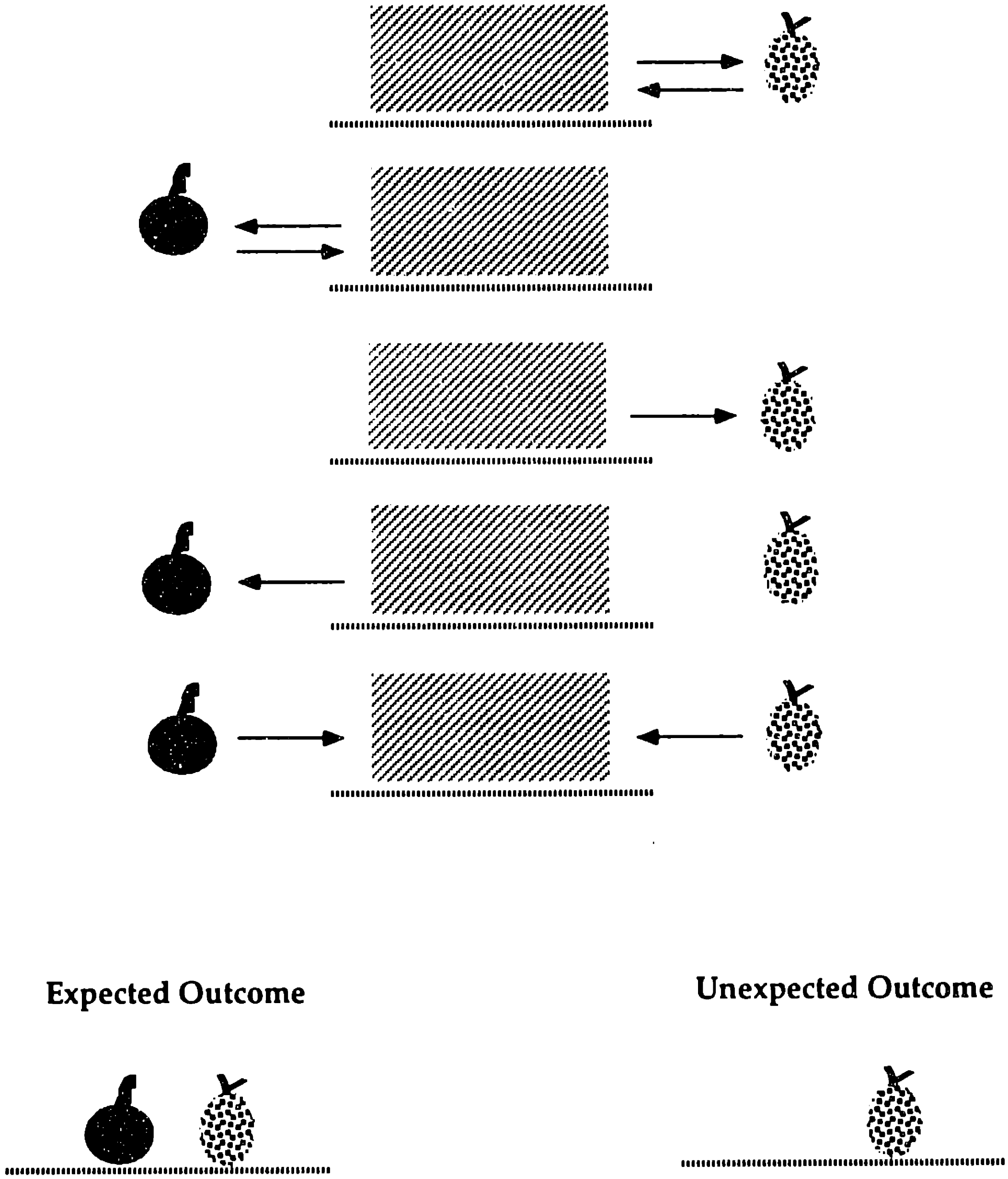
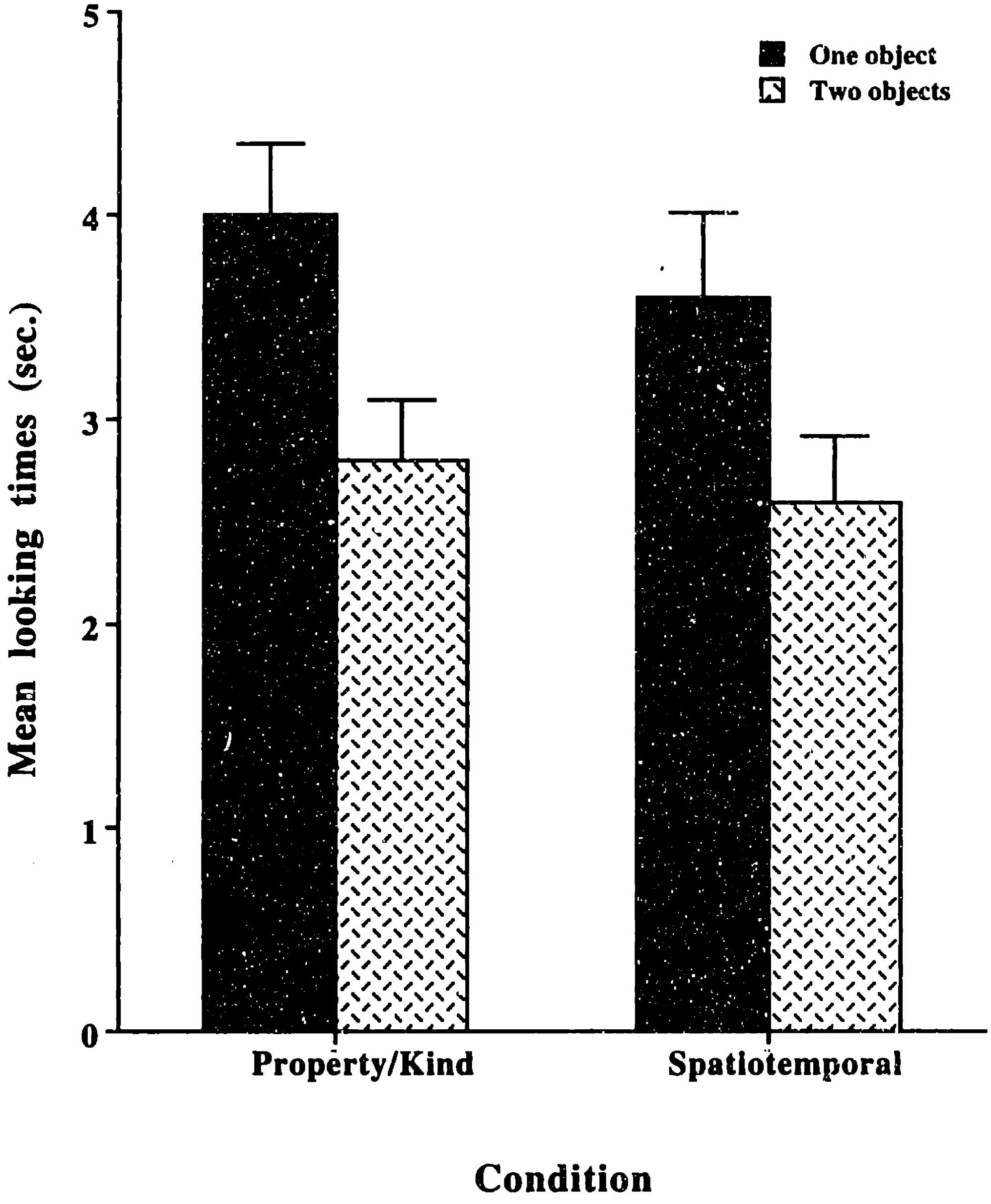


Figure 3



5
4
3
2
1
0
Mean looking times (sec.)
■ One object
▨ Two objects
Property/Kind
Spatiotemporal
Condition

Figure 4

Chapter V

Conclusion

Under the psychological viewpoint, the domain of number is of particular interest because of its nature. Number is an abstract concept, an abstract descriptor for sets of objects which are apprehended in the world. A variety of questions in this domain has motivated the studies presented herein. In the present chapters, we investigated (1) the nature of the representations underlying infant spontaneous numerical knowledge as evinced by the preferential looking and violation of expectancy methodology; (2) whether nonhuman primates would present the same rudimentary spontaneous numerical representations found in human infants and (3) what criteria nonhuman primates utilize for the construction of object individuation and numerical identity.

In Chapter II, we presented young infants with an addition 1 + 1 task in which several manipulations were perfomed to verify what kind of representation is underlying infants' numerical representations. We discussed the symbolic models presented in the literature, the numeron-list account (Gelman & Gallistel, 1978) and the accumulator model (Meck & Church, 1983) and presented the object-file model as a good candidate to account for such representations. In order to accomplish this, we contrasted tasks in different timings and varied different factors. We found that 8- and 10-month-old human infants succeed in object-first tasks, but younger infants do not succeed in the screen-first task. Details of experimental procedure as the timing of the placement of the screen (Experiment 1), the number of screens (Experiment 2), and the grouping of the objects (Baillargeon et al., 1995) affect success in infant addition experiments. These results suggest that at least three factors may influence the robustness of the mental model the infant constructs of the objects in the array: 1) a model based on perceptual experience is more robust than one created in imagery; 2) each update of a mental model decreases its robustness; 3) perceptually available markers of distinct locations increase the robustness of models of distinct hidden objects. A fourth factor plausibly influences robustness of infants' mental representations of the objects in an array: the complexity of the final model the infant must hold in memory. That is, models of one object are likely to be more robust than those with two objects, which in turn are likely to be more robust than those with three objects, even though infants can, as can adults, hold three individuated entities in mind at once.

It is difficult to see how the symbolic counting models would account for subtraction being easier than addition. In subtraction, the counter must be incremented to the maximum value of the set before an object is removed, and then adjusted downward. During addition, the counter is simply incremented to the maximum value of the final set. However, the object file model discussed herein predicts that subtraction will be easier than addition for pairs that differ in the number of items in the final model (e.g., 1+1 vs. 2-1; 2+1 vs. 3-1). Models of "2" constructed in imagery are less robust than models of "1"; models of "3" constructed in imagery are less robust than models of "2". Also, it is plausible that operations on models created from perceptual experience which involve deletions of objects in the model are easier, and thus yield more robust representations, than those which involve additions of objects to the model.

The object file model, as we have sketched it in Chapter II, embodies a construction which entails the notion of "robustness of the model". The idea is that the factors that decrease the quality of a model lead, with varying probabilities, to the baby's inability to maintain a short term memory representation of what is on the stage, just as a variety of factors interfere with an adult's short term memory representation of a set of visual figures, e.g., confusability of items, modality specific interference, etc. (Allport, 1989). Recently, Munakata, McClelland, Johnson & Siegler (1994) have appealed to and modeled strength (or robustness) of a representation of a hidden object as a possible account of greater estimates of infants' knowledge from looking times than from reaching measures.

The effects of order of screen placement, number of screens, grouping of objects and addition versus subtraction are consistent with the object file account of infant performance in the addition and subtraction experiments, and they are not consistent with the accumulator or numeron list models. On the latter models, the infant increments a counter for each new object introduced into the array, arriving at a symbolic representation of their number. Then when the screen is removed, the infant engages in another count, comparing the results. In such a scenario, there is either no reason for the manipulations studied in these experiments to matter, or, in the case of the addition/subtraction comparison, for the manipulations to favor subtraction.

In sum, we suggest that the weight of evidence currently available supports the proposal that the representation of number underlying infants' successes and failures in the addition experiments consists of mental models of the objects in the arrays. These representations are numerical in that they require that the infant have criteria for numerical identity (the ability to distinguish one entity seen on different occasions from two numerically distinct entities), because a representation that instantiates $(\exists x)(\exists y)((\text{object}(x)\ \&\ \text{object}(y))\ \&\ x \neq y\ \&\ \forall z(\text{object}(z) \rightarrow (z=x) \vee (z=y)))$ is logically equivalent to "There are two entities", and because comparisons among models are on the basis of one-one correspondence among individuals. However, they fall short of symbolic representations of number, as there is no unique symbol for each integer, because there is no counting process defined over them.

In Chapter III, we asked whether nonhuman primates would present spontaneous rudimentary numerical representations, comparable to human infants. The experiments reported there provide evidence that both rhesus monkeys and cotton-top tamarins succeed in a wide variety of in $1 + 1$ tasks. The results with the rhesus macaques extend the results of Hauser et al. (1996) demonstrating that rhesus monkeys have the understanding of the addition operation. The monkeys were able to individuate the actual objects in the box and set up expectations for number of objects to be behind the screen. The experiments with cotton-top tamarins were devised to test for these abilities in a species much more distant, evolutionarily, from humans than are rhesus macaques. The results show that the tamarins also set up the representations of the objects in the arrays and expected to see a determined number of objects when the screen was removed.

In order to compare the spontaneous numerical capacities of nonlinguistic primates to that of prelinguistic infants, the preferential looking/violation of expectancy technique was utilized and shown to be successful both in a population of semi-free-ranging rhesus macaques and with a population (n = 10) of laboratory cotton-top tamarins, a more distantly related species than are rhesus macaques. The cotton-top tamarins payed attention to the events when they were being presented. In addition, the monkeys were shown to understand the addition events and to set up the correct expectancies. The results of these experiments, together with those of Hauser et al. (1996), are suggestive that the rudimentary numerical abilities present in young human infants are widely shared among primates.

In adapting the design to the lab population, methodological problems such as 1) changing a between-subjects design into a within-subjects design; 2) finding the appropriate stimuli that would keep the monkey within task; or 3) risking lose the monkeys' interest due to overtesting were solved. One advantage of the use of this technique with lab animals over human infants is that the studies can be more carefully controlled for experimental effects. The laboratory situation of the animals, on the one hand, allows for the control of the experience the animals undergo along testing. For example, experimenters in the lab know exactly the experiments, amount of training, and performance data of each individual, which can be useful to observe individual differences, individual experience, group experience and patterns of successes and failures. In the case of human infants, on the other hand, there is no possible means to control for such aspects.

The investigation with more distantly related species than apes presented in Chapter III provided the possibility of expanding the characterization of cognitive primitives beyond the realm of the chimpanzee. The majority of the studies in comparative cognition have been performed with chimpanzees because, at first, it was believed that chimpanzees were putatively the smartest of all nonhuman primate species. Investigations with such a species would allow researchers to find correlates between their capabilities and our own (Ferster, 1964). More recently, with the advent of genetic research, chimpanzees have been shown to be the closest related species to humans, sharing with us 95% of their genetic code (Sibley & Ahlquist, 1984). It seems, thus, that putative intelligence and phylogenetic proximity have impelled a vast amount of research with chimpanzees, addressing questions which range from linguistic abilities (Gardner & Gardner, 1969, 1975; Premack, 1970; Savage-Rumbaugh, Rumbaugh & Boysen, 1980; Terrace, Pettito, Sanders & Bever, 1979), theory of mind (Woodruff & Premack, 1981), to numerical abilities (Boysen, 1993; Matsuzawa, 1985; Washburn & Rumbaugh, 1991), in the realm of cognitive research. As researchers in comparative psychology commonly point out, the inherited architecture of the human mind is a product of the evolutionary process (Byrne & Whiten, 1988; Cheney & Seyfarth, 1990; Gallistel, 1990; Gallistel & Gelman, 1992; Klein & Starkey, 1987; Povinelli, 1993; Povinelli & Eddy, 1996; Premack, 1976). The idea is that if human capabilities present in early infancy can be shown in species as distant as tamarins, then presumably such abilities are widely shared and can perhaps be considered as cognitive primitives in phylogeny (Hauser & Carey, in press). The findings presented in Chapter III suggest that primates as distant as cotton-top tamarins possess the same primitive spontaneous numerical abilities that do human infants.

Chapter IV investigated whether nonhuman primates construct object kinds and what criteria they use for object individuation and numerical identity. We conducted two experiments in which the monkeys were required to use property/kind information or spatiotemporal information to individuate objects and trace numerical identity through time. The main results of this study are the monkeys' successes in both PK and ST conditions, contrary to results with human infants which show that they individuate objects using primarily spatiotemporal information. Taken together, these data show that the monkeys were sensitive to the presence of two distinct objects behind the screen and succeeded in using property/kind information alone to individuate the objects and set up expectations about the number of objects to be behind the screen. The evidence provided by the present results is consistent with the possibility that the monkeys use property/kind differences between objects to individuate them.

The present findings show that nonhuman primates spontaneously represent objects. The possibility of investigating spontaneous cognitive abilities of nonlinguistic creatures, such as rhesus macaques, was proven successful with the use of the preferential looking and violation of expectancy method. Spontaneous representations such as the ones researched here, in general, are not assessed in methods that utilize training (Blois & Novak, 1994). The rhesus monkeys set up spontaneous representations of distinct objects without any training. These results also demonstrate that the monkeys represented distinct objects under unconstrained field conditions. Unlike a laboratory situation, where control of the experimental setting can be fulfilled, the experimental situation of this study was uncontrolled in that the monkeys were free to do whatever they wanted. Interactions with other animals and natural disinterest in the task interrupted experimental sessions.

These results further confirm the findings that nonhuman primates have object permanence (Antinucci, 1989). Rhesus monkeys, as also in the case of Tinkelpaugh's (1928) cyno monkey, establish representations of distinct individuals. They individuate objects and understand the object concept because they set up representations of two hidden objects -- namely, they looked longer when there was only one object revealed upon removal of the screen. They use spatiotemporal and property/kind criteria for the individuation of such objects. Primarily, the results suggest that the monkeys believe that objects do not cease to exist when they are occluded from view. The results also show that the monkeys established individuals in the first place. In the present study, the objects were hidden behind the screen all the time. They never saw the experimenter put the objects behind the screen. They used the information provided by the emergences of each object -- both property/kind and spatiotemporal -- to infer that two distinct individuals existed behind the screen.

The data presented here seem to show no evidence for the hypothesis that the capacity to represent object kinds is part of the human species-specific linguistic capacity. At least, the experiments are consistent with the hypothesis that nonhuman primates represent object kinds in the absence of a linguistic system. The ability to individuate the objects on the basis of spatiotemporal and property/kind information is genuinely spontaneously present in rhesus macaques, contrary to the prediction that the language faculty would be driving the construction of object kinds. It is possible that the notion of object kinds is not distinctively human, and thus may be part of an evolutionarily ancient adaptation that predates the emergence of human linguistic capacity.

Alternatively, there is also a possibility that the monkeys individuated the objects on the basis of object-with-carrot-properties and object-with-piece-of-squash-properties, not necessarily on the basis of the kind information (carrot and piece-of-squash). In the property/kind condition, the monkeys may be using the differences between something being orange and shiny (carrot properties) versus yellow and dull (piece of squash properties) to realize that there are two objects behind the screen. If the monkeys do not represent object kinds, then it may be that there is something specific about humans. Perhaps the difference between the human infants and the rhesus monkeys in that human infants are, by virtue of being humans, prelinguistic, whereas primates do not possess a language faculty.

The question of whether the monkeys' used kind information to individuate distinct objects is still left open. It may be the case that monkeys use properties to individuate the objects, and certain properties are more salient (such as shape) than others. As suggested in Chapter IV, the infants seem to use shape information before they use color or texture, which implies that shape may be guiding the infant developing language comprehension capacity since shape marks object kinds. A possibility is that nonhuman primates individuate objects irrespective of properties. For example, it is possible that the monkeys will be able to individuate a red carrot and a yellow carrot as well as human adults would. The question is not whether monkeys represent object properties because there is evidence they do from the property/kind condition. It may be that a property such as shape, salient to human infants, is not as salient to monkeys. Further tests are needed to find out what kinds of properties, and to what degree, nonhuman primates use for individuating objects.

The results of the studies presented herein are intriguing and strongly suggest that spontaneous rudimentary numerical representations seem to be widely shared amongst primates. These fidings are enlightening and represent a unique contribution to the study of cognitive abilities in nonhuman primates. This study opens up a fruitful opportunity for the development of research in comparative cognition work with nonhuman primate species.

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