Relational Spatial Reasoning by a Nonhuman: The Example of Capuchin Monkeys

Dorothy M. Fragaszy
Department of Psychology, University of Georgia

Sarah E. Cummins-Sebree
Behavioral Sciences Department, Raymond Walters College, University of Cincinnati

The authors review spontaneous manipulation and spatial problem solving by capuchin monkeys to illuminate the nature of relational reasoning (wherein two or more elements of a problem or situation are considered together to arrive at a course of action) that these monkeys use in goal-directed activity. Capuchin monkeys master problems with one, two, or three spatial relations, and if more than one relation, at least two relations may be managed concurrently. They can master static and dynamic relations and, with sufficient practice, can produce specific spatial relations through both direct and distal action. Examining capuchins' spatial problem-solving behavior with objects in the framework of a spatial relational reasoning model leads to new interpretations of previous studies with these monkeys and other nonhuman animals. The model produces a variety of testable predictions concerning the contribution of relational properties to spatial reasoning. It also provides conceptual linkages with neurological processes and cognitive analyses of physical reasoning. Understanding relational spatial reasoning, including tool use, in a wider view is vital to informed, principled comparison of problem solving and the use of technology across species, across ages within species, and across eras in human prehistory.

Key Words: spatial reasoning, problem solving, cognition, *Cebus apella*

Reasoning about spatial relations (in which two or more elements of a problem or situation are considered together to arrive at a course of action), especially multiple relations and relations among moving bodies, is challenging, as anyone who has studied geometry, stereometry, trigonometry, mechanical engineering, astronomy, or a host of other fields with a strong spatial component knows well.[1] Nevertheless, such reasoning is a ubiquitous feature of human cognition. Reasoning about spatial relations includes consideration of objects and surfaces with reference to each other (such as evaluating landmarks), movements of the body in space in relation to objects and surfaces (such as how to move around obstacles, choose a path, etc.), and movements of objects by the body (such as how to bring object *X* into contact with object *Y*). Human history is replete with fundamental advances in technology that relied on the insight that the movement of an object in one place produces orderly movement with mechanical advantage of the same object in another place (e.g., a hammer, wheel, fulcrum, or lever) or at a distance from the body (e.g., a spear); that placing two or more objects in specific relation to each other either produces a new kind of material (e.g., braiding rope, weaving fiber) or allows one object to be used to fix another in place (e.g., tying with rope, fastening with a peg); or that the movement of one object can produce orderly movement in another object (e.g., the gear of a pottery wheel). No doubt anthropologists or engineers can expand on this theme ad infinitum; this short list is what comes to the mind of oft-times mechanically challenged psychologists.

Humans, especially with appropriate training and practice, can clearly reason effectively about spatial relations, even abstract spatial relations (although some of us have more aptitude for this activity than others!) to arrive at effective action to solve problems. Just as clearly,

Authors' Note: We thank Jeff Lockman, Hideko Takeshita, Elisabetta Visalberghi, Amy Fuller, and Patricia Potì for many discussions about these issues. Financial support was provided by Grants HD 38051 and 06016 to Georgia State University, and NSF Grant BCS 0125486 to Dorothy M. Fragaszy. Correspondence should be sent to Dorothy M. Fragaszy, Department of Psychology, University of Georgia, Athens, GA 30602-3013; e-mail: doree@uga.edu.

Behavioral and Cognitive Neuroscience Reviews
Volume 4 Number 4, December 2005 282-306
DOI: 10.1177/1534582306286573

mastering spatial reasoning presents an enormous and continuing challenge—the technological insights mentioned above occurred over millennia. Consider, for example, the critical appearance of flaked stone tools in human prehistory. The requirements for relational reasoning are a substantial part of the challenge of using as well as making flaked tools and thus are part of the reason that flaked tools represent a watershed in human technological evolution. Toth (1987) categorized flaked or knapped stone tools made by hominid ancestors in terms of the spatial and force relations between striking stone and core stone that must be mastered by the tool maker. A stone flake with a sharp edge suitable for cutting or scraping, for example, is made by striking a core stone with another stone. It may seem to a 21st-century reader a simple enough task, even if one has not tried to do it, but to obtain that flake, one should strike the core at a specific point with respect to its center and circumference and at a specific angle with respect to the longitudinal axis of the core. Thus, there are two spatial relations to manage concurrently when flaking a stone, and mastering management of both at once, along with producing the proper striking force, takes contemporary adult humans some hours of concerted practice to master to an adequate degree of proficiency (Toth, 1987). Creating stone tools with additional worked surfaces involves managing many additional relations, concurrently and successively, during stone knapping (Toth, Schick, Savage-Rumbaugh, Sevcik, & Rumbaugh, 1993). The relational complexity of various tools is one explanation given for the ordered appearance of stone tools of different varieties in the paleoarcheological record (Wynn, 1993). Knapping hard materials to a precise product remains a challenging task for humans. For example, knappers of long carnelian cylindrical glass beads used as jewelry for 3 millennia in Gujarat, India, require 7 years of apprenticeship to become masters (Roux, Bril, & Dietrich, 1995).

The challenge of spatial reasoning is also evident in its gradual appearance during ontogeny. Young children move from unifocal attention on a single object to mastering integrated action with two hands, with one object and then with more than one object, to acting with one object on another, and so on to the skilled and culturally appropriate use of objects as tools (Bushnell & Boudreau, 1996; Connolly & Dalgleish, 1989; Corbetta & Thelen, 1996; Fagard, 1996; Lockman, 2000). In the young child, this progression coincides with increasing mastery of movement of the body, itself a challenging relational problem (Bernstein, 1996; Berthoz, 2000; Thelen & Smith, 1994). Development of walking and improving mastery of dynamic balance generally opens the possibilities of many new actions involving moving the body in relation to objects and spatial layouts in locomotion (detours: Lockman, 1984; slopes: Adolph, Eppler, & Gibson, 1993), reaching (Spencer, Vereijken, Diedrich, & Thelen, 2000), and manual actions producing relations between objects, such as banging (Lockman, 2000) and drumming (Brakke, Fragaszy, Simpson, Hoy, & Cummins-Sebree, in press).

Descriptions of tool use by young children consistently highlight the initial difficulty for the child of managing the spatial relations embodied in the problem (Bushnell & Boudreau, 1996; Lockman, 2000). Connolly and Dalgleish (1989) articulated the challenges for the young child of controlling the multiple concurrent and sequential spatial relations involved in using a spoon. For example, during early efforts to use a spoon to carry food, children do not effectively maintain the horizontal orientation of the bowl of the spoon; consequently, they frequently spill the contents of the spoon before it gets to their mouths. Cummins-Sebree, Fragaszy, Hoy, Simpson, and Chamnongkich (2004, unpublished data) noted that children from 12 through 24 months are less accurate at striking a cylinder when they hold the handle of a mallet than when they strike the cylinder with a cube held in the hand. The handle holds the head of the mallet a distance from the hand. Moving the mallet to the cylinder thus involves managing a different (and less familiar) spatial relation than moving the cube in the hand to the cylinder.

Given that relational spatial reasoning is an ancient, fundamental, and ubiquitous feature of human cognition, comparative study of this phenomenon can contribute to our understanding of its origins and elaboration. In this review, we consider evidence indicating that capuchin monkeys, a genus of monkeys from South America, reason about spatial relations in the course of solving experimental problems involving moving objects in two- and three-dimensional space. Capuchins are an apt genus for this enterprise for several reasons, most notably because they spontaneously manipulate objects in ways that produce spatial relations between objects and surfaces and because they spontaneously use objects as tools (see Fragaszy, Visalberghi, & Fedigan, 2004, for detailed review). We will argue that the joint occurrence of these characteristics is no coincidence. Both characteristics are anomalous among monkeys but are shared with humans, and they indicate the potential for some degree of humanlike spatial reasoning in capuchin monkeys. Thus, capuchins offer one of the best opportunities to find elements of spatial cognition shared with humans, without the complicating factor of language. Eventually, someone will be able to write a similar review including the fascinating New Caledonian crows, the ultimate tool users in the avian order (Hunt, 1996; Hunt & Gray, 2003, 2004; Rutledge & Hunt, 2004;

Table 1: Properties of Spatial Relations Produced, Used, or Embodied in Action

Property	*Definition*	*Variants*
Number of spatial relations	Number of elements in action event	1, 2, . . .
Relation to body	Positioning of object in space	Direct vs. indirect
Specificity	Precision required for action	Permissive (nonspecific) vs. specific
Temporal nature of control	Length of time for contact	Static vs. dynamic
Temporal order of production	Order of actions in time	Sequential vs. concurrent

NOTE: For each property, the alternative ends of the spectrum of possible variants are given.

Weir, Chappell, & Kacelnik, 2002), but at present, this is an intriguing goal for the future.

A RELATIONAL MODEL OF SPATIAL REASONING

One of our purposes in writing this piece is to present a conceptual model of spatial reasoning. Briefly, the model builds upon ideas presented by Lockman (2000), Bushnell and Boudreau (1996), and others who have conceptualized object manipulation from the standpoint of actions in space and time. Our model of spatial reasoning incorporates the number of spatial relations as well as four properties of the spatial relations embodied in a problem or action: (a) specificity, (b) duration, (c) stability over time, and (d) the temporal relation between the production of different relations (see Table 1). The number of spatial relations is determined by how many external elements (not parts of the body) participate in a given action or event. For example, scraping frost from a windshield with a scraper tool contains one relation produced by the user: between the scraper and the windshield. Starting to hammer a nail into a board with a hammer requires that the actor produce two relations: (a) between the nail and the board and (b) between the hammer and the nail.

Let us clarify the properties of spatial relations listed in Table 1 as important in spatial reasoning. We start by discussing these spatial relations as they pertain to instrumental actions, and we begin with the property of directness with respect to the body. Instrumental actions involve rearranging or producing new spatial relations among the body, objects, and environmental features. Placing a part of the body on an object or surface produces a direct, egocentric spatial relation, as in stamping one's foot on the ground or picking up a coffee cup. Positioning an object with respect to a feature of the environment produces an indirect, allocentric spatial relation. For example, one produces an indirect spatial relation when one places a cup on a saucer. Many instrumental actions involve producing indirect relations to achieve other indirect relations. For example, a golfer produces an indirect spatial relation between golf club and ball when he or she strikes the ball with the club, in an attempt to control (a second) indirect relation between the ball and the cup. Following Lockman (2000), we propose that reasoning about and producing a direct spatial relation between an object and the body is in principle easier than producing an indirect relation between an object and some other feature of the environment.

Specificity, another property in our model, refers to the precision of the spatial relation between two elements. Greater specificity entails the use of more attentional resources: to detect or plan the relation prior to action, to produce a finely adjusted motor act, and to monitor the outcome of action. Thus, difficulty of a problem increases as specificity of spatial relations involved in the problem increases. For example, using an ice scraper to remove frost from a windshield involves nonspecific relations; wide variations in each swipe of the ice scraper are still effective. On the other hand, hitting a nail with a hammer involves producing a specific relation (unless one does not mind creating divots in the board or bruised thumbs). Although specificity is treated as a unitary binary element in Table 1, this is a simplification for expositional purposes. It matters a great deal to the actor whether the specificity can be produced during the action (as in striking the nail accurately) or whether the specificity must be produced in advance of action (by orienting a specific side of an object toward another, for example). Anticipatory action to produce specific orientations prior to the relational action may tap different processes than does accommodation during action to specific spatial requirements (Berthoz, 2000).

Effective spatial reasoning must take into account at least two temporal properties. The first is relevant to any spatial relation: the temporal duration of control required for action. A static relation, once produced, requires no further action to maintain it, whereas a dynamic relation requires continuous action that is monitored over time to maintain the relation. For example, a flat object placed with its center of mass on a horizontal surface does not move once it comes to rest unless it is acted on again. This is a static relation, and once the object is placed, the actor does not need to continue to hold it for it to remain stationary. On the other hand, if the object is placed on a slanted surface, the actor must continue to hold it to keep it in place. This is a dynamic relation. Dynamic relations are more demanding than static relations, other things being equal, because they require continuing action and monitoring, whereas static relations do not. The child's difficulty maintaining a spoon traveling from bowl to mouth in a horizontal orientation exemplifies this point.

The second temporal property applies when a problem involves more than one spatial relation. In such a circumstance, spatial relations may be produced concurrently or sequentially. A sequential order of actions permits the actor to focus on one spatial relation at a time; for example, getting a box from a high shelf with a steady stepstool requires putting the stool in front of the shelf, then standing on the stool, and then reaching for the box. Each action is the sole focus as it is performed. A concurrent order of actions involves focusing on multiple spatial relations at the same time; for example, getting a box from a high shelf when only a swivel chair is available for use as a step requires focusing not only on reaching the box but also on keeping the swivel chair as still as possible while reaching for the box. In this example, the dynamic relation between chair seat and shelf must be maintained over time by the actor to afford an effective reaching position.

In our model, reasoning about or producing sequential relations is less demanding than is reasoning about two or more relations concurrently, and each additional concurrent relation increases the difficulty of a problem. The premise that concurrent attention to two relations is more difficult than sequential attention to the same relations is shared with neo-Piagetian models of cognitive development. These models specify that integration of relational elements in a given problem space appears, developmentally, after sequential management of these elements (e.g., Case, 1992; Case & Okamoto, 1996).

Attention to the role of temporal aspects of spatial relations in spatial reasoning is an important feature of our model. Time is an important element in spatial reasoning in several ways—it is implicated in prospectivity (*sensu* von Hofsten, 1993), in maintaining attention on the current action, and in requiring continuance and adjustment of action when a dynamic process is at work (e.g., holding an object against gravity, adjusting pulling force as friction changes). Time is also a critical element at the level of neurological processes affecting spatial reasoning, such as multisensory perception and processes binding action and perception (Ballard, Hahoe, Pook, & Rao, 1997; Hommel, Müsseler, Arschersleben, & Prinz, 2001; Jackson, 2001; Soto-Faraco & Kingstone, 2004). Our model affords a conceptual bridge between these aspects of neuroscience and cognitive concerns with spatial problem solving.

In the following sections, we review relational spatial reasoning by capuchins in four domains for which we have a reasonable body of evidence: (a) spontaneous manipulations with objects, (b) instrumental actions, (c) using objects as tools (a special case of [b]), and (d) visual perceptual judgments about moving objects. Our review covers primarily reasoning about actions and events in near space (within arm's reach). Table 2 presents an overview of the behaviors we will discuss, noting the number of spatial relations and the relevant properties of the relations embodied in the tasks.

Application of the Relational Spatial Model to Combinatorial Manipulation in Capuchins

Frequently, capuchins spontaneously combine objects and surfaces or objects and other objects, which we label "combinatorial actions." Even though such activities are a small proportion of all manual activity in both natural and captive settings (Byrne & Suomi, 1996; Fragaszy & Adams-Curtis, 1991; Fragaszy & Boinski, 1995; Natale, 1989), they feature regularly in normal foraging and exploratory manipulation. Combinatorial actions are particularly interesting to behavioral scientists because (a) these actions allow the monkeys to gain access to foods they could otherwise not get through direct biting and pulling; (b) they require the coordination through action of objects and/or surfaces relative to each other, a feat not routinely accomplished by nonhuman primates; and (c) these actions are the precursors of using tools, another distinguishing characteristic of capuchins.

To bring some conceptual order to the varieties of combinatorial actions produced by capuchins, we class them by two orthogonal factors: the number of spatial relations embodied in the actions, and the degree of specificity of the spatial relation(s) produced by the actor. The overwhelmingly most common combinatorial actions capuchins produce in captivity and in nature, rubbing and pounding an object against a substrate, involve a single spatial relation. In most cases, these are nonspecific combinations because the substrate is much larger than the object brought against it and the monkey can bring the object into contact with the substrate anywhere on its surface.

In our model, specific spatial relations are more difficult for the actor to achieve than nonspecific relations because they require producing a particular spatial relation (such as alignment) between object and substrate or other object. We have many examples of capuchin monkeys producing a single specific relation between an object and a fixed substrate. Izawa and Mizuno (1977) provide a striking illustration of specific combination in their descriptions of tufted capuchin monkeys opening hard fruits by pounding them against the protruding

Table 2: Categorization of Spatial Relations Involved in Reviewed Tasks

		Properties of Spatial Relations			
Task	*No.*	*Specificity*	*Temporal Order*	*Relation to Body*	*Temporal Nature of Control*
Anticipate end point of object moving on surface	1 or 2	Specific	NA or sequential	Indirect	Mixed; dynamic when object encounters irregularity (gap or barrier) in surface
Track spatial relation between landmark, bait	1	Specific	Specific	NA	Static
Move joystick to move cursor (a) to stationary goal (b)	2	Nonspecific to specific	(a) Concurrent, (b) Concurrent	(a) Indirect, (b) Indirect	(a) Dynamic, (b) Static
Move joystick to move cursor (a) to moving goal (b)	2	Specific	(a) Concurrent, (b) Concurrent	(a) Indirect, (b) Indirect	(a) Dynamic, (b) Static
Move joystick to move cursor (a) through mazes (b)	2	Specific	(a) Concurrent, (b) Concurrent	(a) Indirect, (b) Indirect	(b)Static between cursor and goal; (a) Dynamic between joystick and cursor
Reach for object using mirror image to guide reaching	2	Specific	Concurrent	Indirect (looking at object in mirror); direct (reaching for food)	Dynamic
Connect food with continuous substrate	1	Nonspecific	NA	Indirect	Dynamic (rubbing) or static (pounding)
Connect one object with single surface at particular point	1	Specific	NA	Indirect	Dynamic (pushing object through aperture) or static (pounding fruit against node of tree trunk)
Connect two objects, one held in each hand, by banging	1	Specific	NA	Indirect	Dynamic or static (depending on whether one hand is stationary)
Spontaneous creation of groups of objects	1	Nonspecific	Sequential	Direct	Static
Combining nesting cups	1	Specific	Sequential	Indirect	Static
Pull in a cane with food inside the hook, straight part of the cane within reach	0	Specific	NA	Direct	Static
Pull in cloth with food on the cloth	0	Specific	NA	Direct	Static
Probe into an opening with a stick (“dip”)	1	Specific	NA	Indirect	Static
Pound a stone on a nut fixed on a surface	1	Specific	NA	Indirect	Static
Put a stick into a tube (a) then push food out of a tube with a stick (b)	1	Specific	(a) Sequential, (b) Sequential	(a) Indirect, (b) Indirect	(a) Static, (b) Dynamic
Pull in an object with stick when stick must be repositioned to maintain contact with food during pulling	1	Specific	NA	Indirect	Dynamic
Pound a loose nut with stone, where stone may move when struck	1	Specific	NA	Indirect	Dynamic
Pound a stone on a nut (b) placed (and released) on a stable anvil surface(a)	2	Specific	Sequential	Indirect	(b) Dynamic, (a) Static
Put a stick into a tube (a) then Push food out of the tube (b) while avoiding a hole in the tube(c)	3	Specific	(a) to (b) Sequential, (b) Concurrent with (c)	(a) Indirect, (b) Indirect, (c) Indirect	(a) Static, (b) Dynamic, (c) Dynamic
Pull food with rake (a) while avoiding hole in surface (b)	2	Specific	Concurrent	(a) Indirect, (b) Indirect	(a) Dynamic, (b) Dynamic
Pound a stone on a nut (a) held in place by hand on a slanted or otherwise unstable anvil surface	2	Specific	Concurrent	(a) Indirect, (b) Direct	(a) Dynamic, (b) Dynamic

NOTE: NA = not applicable.
2) No. = number.
3) The direction relation between hand(s) and an object, which permits the actor to move the object in many of the tasks listed here, is not included in the notation of Number in this table. The spatial relations listed in the Number column are in addition to the relation between hand and object.
4) Specificity refers to the most constrained (most specifc) relation in cases where more than one relation is involved.

growth node of a bamboo trunk. Sometimes, monkeys consistently pound the long axis of an elliptical or linear object perpendicular to a tree limb or other relatively straight edge (Boinski, Quatrone, & Swartz, 2001; Panger, 1998). Other examples of producing a single specific relation come from monkeys in captivity that align a latch with the fixed edge of the door so that they can open the door (Simons & Holtkotter, 1986) and monkeys that align the edges of an object to pass it through an aperture with the same contours (Fragaszy & Crast, 2004). The monkeys have no difficulty passing objects through apertures so long as the object to be passed has a circular or symmetrical outer contour. In this case, aligning a single edge will serve to align the whole object. However, the monkeys are inefficient at aligning asymmetrical objects (such as a cross with one long axis and one short axis). The latter task requires managing two spatial relations concurrently (two axes of the object and aperture).

Combining two loose objects with each other requires producing a single relation. We have a few examples of this kind of activity from monkeys in nature. White-fronted capuchins in Peru sometimes bang two hard nuts against each other (Terborgh, 1983), and wedge capped capuchins in Venezuela bang two snails against each other occasionally (Fragaszy, personal observation). Capuchins bang two small objects together rather commonly in captivity (Fragaszy, personal observation). A compelling anecdotal example of a specific action with two objects producing a single relation in a captive capuchin monkey comes from Fragaszy's laboratory, where one monkey habitually holds one pellet of chow in his teeth, long axis downward, and a second piece in both cupped palms, long axis horizontal, as he rotates his head back and forth to grind the pellets against one another. At the end of a grinding sequence, the monkey licks up the powdered chow he has produced.

Combining one object with another, and concurrently or successively combining the paired set with a third object or substrate, produces two relations. We have one example of wild capuchin monkeys producing or managing two relations while manipulating objects. Capuchin monkeys in Piauí state, Brazil, routinely pound open nuts placed on stones by using a second stone (Fragaszy, Izar, Visalberghi, Ottoni, & Gomes de Oliveira, 2004; Ottoni & Mannu, 2001, described a similar phenomenon in semifree monkeys). Note that using an anvil stone and a hammer stone to open a nut transported to the work site is the most structurally complicated form of tool use observed routinely in wild chimpanzees (Matsuzawa, 2001). It is thus thought-provoking that the first discovery of routine use of tools by a population of monkeys involves stone anvil and hammer use. We come back to tool use, and this example of it, in more detail later in this review.

Organizing Multiple Objects

Spontaneous constructions. Spinozzi and Natale (1989) studied how capuchins organize activity with multiple objects by providing a monkey with a set of six small objects (cups, crosses, rings, and sticks) shaped from four different materials. Each set of objects belonged to one of three conditions: (a) two sets of three identical objects that differed in one property only (e.g., three wood cups and three wood crosses), (b) three identical objects that differed in both form and material (e.g., three wood cups and three acrylic rings), and (c) six objects of three different forms and two different materials, or vice versa. The individuals were free to do as they liked with the objects, without reward or interference, for a period of 5 minutes. The monkeys encountered each condition once per session, over eight test sessions.

One of the aspects of the monkeys' activity that interested the experimenters was the way they moved objects into proximity (closer than 10 cm) with one another (i.e., more than one object within arm's reach) or moved them apart from each other. When young children are given objects like this, they routinely construct and disassemble sets of two, three, or more objects, and even assemble sets of sets in a hierarchical organization (such as placing all metal objects in one place, ordering them by shape, then placing all wooden objects together, ordering them also by shape). These actions presage the logical operations used in addition, subtraction, multiplication, and so on (Langer, 1981, 1985). If object placements were random, there would be smaller numbers of multiobject sets than two-object sets, and sets would not likely overlap in time or follow one another in close temporal sequence. Spinozzi and Natale (1989) found that two 4-year-old capuchin monkeys placed three or more objects in 40% of their sets, roughly equivalent to what human children of 15 months do in similar circumstances, indicating nonrandom assemblies. Capuchin monkeys made temporally sequential sets in 101 instances out of 129 sets (82% of their constructions) but rarely made simultaneous sets (14 of 129 sets; 11% of constructions) (Potì & Antinucci, 1989). Human children show a different pattern from their 2nd year onward; they increasingly compose simultaneous sets. Producing simultaneous sets (as humans do) enables exploratory composing of related sets. The monkeys' limitations (compared to young humans not yet 2 years of age) to managing objects within one set at a time are evident in these findings.

Specific constructions. Other methods of probing individuals' organizational skills involve providing subjects with a goal as opposed to the unguided (spontaneous) manipulative actions analyzed by Spinozzi and colleagues. A classic test of children's developing spatial organizational skills is whether they can seriate sets of nesting cups (Greenfield, Nelson, & Saltzman, 1972), an activity that children do spontaneously in play but can also easily be prompted to perform. Initially, young children (about a year old) simply pair two cups. Later on, they make multicup structures, eventually managing frequently (in their 3rd year) to order the cups correctly. Later, in their 3rd or even 4th year, they can routinely insert a middle cup held out from the rest into its proper place in an already-seriated set. Nesting seriated cups requires producing a series of specific relations between each cup inserted into another, in turn. It can be thought of as a sequential series of first-order, specific, indirect, static relations.

Fragaszy and colleagues (Fragaszy, Galloway, Johnson-Pynn, & Brakke, 2002; Johnson-Pynn, Fragaszy, Hirsh, Brakke, & Greenfield, 1999) presented nesting cups to adult capuchin monkeys and chimpanzees and to children between 11 and 21 months of age using the same experimental design as Greenfield et al. (1972). The results were surprising. Capuchins produced fully-seriated sets of five cups on half of the trials in which they got the cups; apes (*Pan troglodytes* and *P. paniscus*) did so on a similar percentage of trials (55%). Both genera of nonhuman primates succeeded more often at seriating the cups than did 11-, 16-, and 21-month-old children (see Figure 1). When given a sixth cup to insert into a seriated set of five cups that they had just constructed, capuchin monkeys succeeded at inserting the extra cup on 56% of these trials; apes, on 36%. Moreover, both capuchin monkeys and apes frequently combined objects using what Greenfield et al. identified as a hierarchical method. That is, they put a small cup into a larger cup, picked up the set, and then placed the set into a third cup or set of cups. Greenfield et al. labeled this way of combining cups *subassembly.* Capuchin monkeys and apes used subassembly on 17% of five-cup trials and 43% of six-cup trials, in which the sixth cup could be any of those between the bottom and the top. Apes in similar conditions used subassembly on 28% and 60% of trials, values not significantly different from the monkeys' values. In all these features, capuchin monkeys and chimpanzees did not differ. The proportional use of subassembly to combine cups was positively correlated with monkeys' and apes' success at inserting a sixth cup, as it was in the Greenfield et al. study with children. The monkeys and apes were more successful at seriating five cups and inserting a sixth middle cup in the seriated set than were all of the very young children (11-21 months old) in the Fragaszy et al. (2002) sample, although they used subassembly far less than did the older (up to 36 months old) children in the Greenfield et al. study who were proficient at seriation.

It is highly unusual to find that chimpanzees and monkeys perform as well as children older than 2 years on a task purported to tap emerging attentional and planning skills. Our interpretation of these findings is that the specific conditions present in this task helped our nonhuman subjects master what is properly appreci-

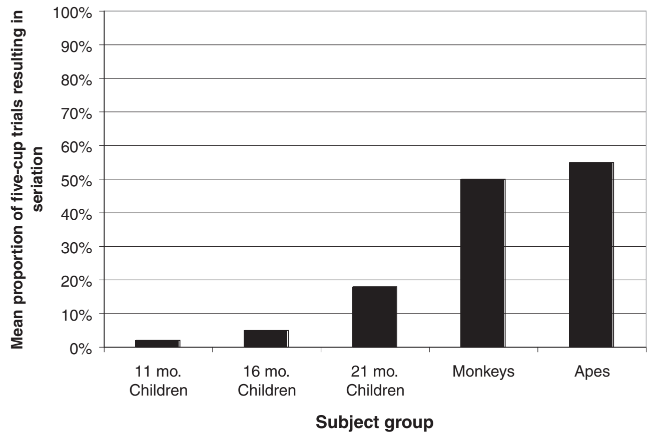

Figure 1: Proportion of Trials in Which Children, Monkeys, or Apes Produced a Seriated Structure of Five Cups.
SOURCE: Reprinted from Fragaszy, Galloway, Johnson-Pynn, & Brakke (2002).

ated as a rather complicated task (Johnson-Pynn & Fragaszy, 2001). This task provides immediate proprioceptive feedback to the actor about the success of each placement when he or she tries to place too large a cup into another (i.e., the cups do not fit together). In this sense the task is physically scaffolded; the properties of the cups themselves provide feedback to the actor about the correctness of the immediately preceding placement.

After much experience with blocked cups, the capuchins and chimpanzees adopt various strategic behaviors that improve their efficiency. Strategic reactions to errors include taking one or more cups out of the existing structure and inserting a different cup or set of cups (Johnson-Pynn & Fragaszy, 2001). Even if the actor does not select the next cup very accurately, as long as one structure is modified but not fully disassembled, eventually the strategy of sequential placement will produce a seriated set. A second aspect of behavior also helps achieve success: capuchin monkeys become quite good at containing the cups in a small working area, using the tail and feet to keep unruly cups from rolling away. Because they have one working stack, persistent action with the one stack permits them to seriate the cups. Thus, although this task appears to require mastery of an ordered sequence, a simpler strategy is also effective: keep working on one stack, and replace a blocked cup with some other cup. This simpler strategy is sufficient to get the capuchin monkey and the chimpanzee (and the young child!) through this task. This is working with one spatial relation at a time: between the current placement and the preexisting top cup.

Overall, capuchin monkeys, like chimpanzees, can produce impressive multicup structures, and they can manage to reassemble sets to include additional elements. Capuchin monkeys (like the other groups of subjects in our experiments) do this without apparent reliance on a systematic spatial strategy; rather, they develop preferred but relatively simple ways of managing multiple objects (keeping them together, replacing a blocked cup with a different cup). Thus, what to an adult human is primarily a spatial problem, with two concurrent relations to judge at each action, was a rather different problem for our subjects and participants.

APPLICATION OF THE RELATIONAL SPATIAL REASONING MODEL TO INSTRUMENTAL ACTIONS IN CAPUCHINS MOVING A CURSOR IN TWO-DIMENSIONAL SPACE

Since Richardson and colleagues (1990) produced a self-paced interactive computerized training system for use with nonhuman primates, individuals of a number of primate species have mastered using a joystick to control the movements of a cursor on a computer screen. Using a joystick involves a physical separation between the locus of action (the joystick handle) and the locus of effect (on the monitor). Thus, to control the cursor, the monkey must learn that moving the joystick produces an effect somewhere else (not at the end of the joystick) and that those distal events have consequences (i.e., that moving the cursor into a “goal box” produces a food treat). Thereafter, the monkey must learn the directional relationship between moving the joystick and moving the cursor, and finally it must learn how to move the joystick to produce the desired movement of the cursor. When skilled, the actor maintains two indirect spatial relations concurrently, using one to control the other: between the cursor and the goal location and between the joystick and the cursor. The relation between the monkey’s action on the joystick and cursor movement is indirect, directionally specific, and nonlinear in that when the cursor reaches a margin, it stops moving even though the monkey continues to push on the joystick. The relation between the cursor and the goal can vary from nonspecific to specific (depending on the size of the goal) and from static (a stationary goal) to dynamic (a moving goal), and it is indirect as well.

Leighty and Fragaszy (2003) studied four capuchin monkeys mastering the joystick system using the self-paced task developed by Richardson et al. (1990). The task involved moving the cursor from a central position on the monitor to a stationary, visually distinctive area (the goal area) on one of the margins of the display. The location of the goal varied randomly over trials. When the cursor reached the goal area, visual and auditory cues signaled success, and the monkey received a favored food treat. The size of the goal decreased systematically as the subject improved its efficiency at reaching it. Initially, the goal was the perimeter of the monitor screen; at the final stage of the task, the goal area was barely larger than the cursor itself. This task embodies a single, indirect, static spatial relation (between cursor and goal) that becomes increasingly more specific. The monkey manages this indirect relation through a direct action between body and joystick.

Two of the monkeys encountered the normal isomorphic relationship between joystick and cursor: pushing the joystick to the left moved the cursor to the left, and pushing the joystick to the right moved the cursor to the right. The other two monkeys encountered the reverse arrangement: pushing the joystick to the right moved the cursor to the left. We used this procedure to test the hypothesis that an isomorphic spatial relation would enhance learning, as has been demonstrated with humans mastering a similar control system.

The four monkeys mastered the task, and as they improved their performance, all four capuchins increased the proportion of each trial in which they visually tracked the movement of the cursor on the monitor, indicating that one important feature they learned early on was that the display provided useful information. Recognizing that they controlled the cursor via the joystick (at first a nonspecific relation) was a critical first step for the monkeys. Then, mastering the directional movement of the cursor followed, to move it effectively to the goal. Fine control of the cursor’s movement was the last feature of the task to be mastered. This order of mastering the elements of using the joystick fits our model of relational problem solving, in that the direct relation of hand to joystick was mastered first, then more gradually the recognition of the indirect relation between joystick and cursor. Controlling the concurrent third relation, the indirect relation between cursor and goal, was mastered last.

The two monkeys mastering the reversed relationship between joystick and cursor learned the task as quickly as the monkeys mastering the normal relationship. When, after having mastered the reversed relationship, these same two monkeys encountered the normal relationship between cursor and joystick, they quickly mastered the new relationship. Apparently, they learned in the first series to control the three relations in this task, including the specific directional relationship between joystick movement and cursor movement, and they learned to use the display to monitor whether the cursor was moving in the correct direction. They had only one element of the set to relearn (the specific directional relationship between cursor and joystick movements) when the task was re-presented with an isomorphic relation between cursor and joystick movement.

Surprisingly, perhaps, to those who have not watched capuchins using joysticks is that all four monkeys displayed a characteristic tilt of the whole torso to the side toward the goal as they moved the joystick laterally, as do other capuchins that are proficient at using a joystick. They did this only when they had mastered this task (see Leighty & Fragaszy, 2003, for further discussion of this phenomenon). Many interpretations of this phenomenon come to mind. Perhaps it has to do with bringing the face closer to the goal area, for example. Our preferred hypothesis at this time is that this behavior reflects the strong inclination to control object movement through a direct spatial relation between body and object; the effort to control the spatial relation somehow expands beyond the hand and arm to encompass the torso and neck. We propose that capuchins' tilting is similar to the body tilting that humans exhibit when they are watching an object that they cannot touch directly in a context where they desire to control the object's movement (as when watching a bowling ball headed for the gutter, a tennis ball headed for the boundary line, or a golf ball headed for the sand trap). Casual observations and inquiries indicate that humans also tilt when playing video games in roughly the same circumstances as the capuchins tilt: when moving an icon in a two-dimensional display using an interactive device (joystick, controller box, mouse, etc.). To our knowledge, no other nonhuman species from the many that have used the same training system tilts while using the joystick. We are most curious to know if tilting is more evident in capuchins than in other nonhuman primates or if other investigators, not knowing what to make of this phenomenon, have neglected to discuss it. We predict that this phenomenon will be present in any species that masters the layered indirect relations present in controlling a cursor by means of a joystick, when the actor is challenged to achieve a specific relation.

After mastering control of the joystick as described above, the monkeys completed a series of other spatial tasks presented in the training paradigm of Richardson et al. (1990). These tasks included intercepting an icon moving across the screen in a semirandom trajectory by "chasing" it with the cursor, tracking a moving circle for up to several seconds by keeping the cursor within the circle as it moves across the screen (at 3 cm/s in our laboratory), moving the cursor around H-shaped "barriers" to reach a goal location, and lastly, "shooting" a moving icon by "firing" at it from a fixed point, where firing was triggered by directional movement of the joystick.

The intercept and tracking task shifted the relation between cursor and goal from static to dynamic. This change produced no serious difficulty for the monkeys. However, the introduction of "walls" in the display that interrupted the cursor's movements (in the absence of proprioception by the hand, on the joystick, of any barrier) initially disrupted performance. In this case, the monkeys had to learn to rely on visual information (only) that the cursor could move no further, despite their action on the joystick that normally resulted in directional cursor movement. Thus, the indirect relation between movement of joystick and movement of cursor within the margins of the display changed from being regular to irregular/conditional: moving the joystick moved the cursor except when the cursor encountered a wall. Eventually, however, the monkeys mastered all these tasks. That they can master these tasks indicates a powerful ability in these species to perceive and produce indirect spatial relations that are significantly different from any previous experience with the natural world.

In sum, using a joystick to move a cursor in a two-dimensional display embodies at minimum three relations: one direct (between hand and joystick) and two indirect (between joystick and cursor and between cursor and goal area). One can manage the task sequentially, by moving the cursor, pausing to check the cursor's spatial relation to the goal, then moving the cursor again. However, efficient use of the joystick involves managing concurrently two indirect relations, one between the joystick and cursor and the other between the cursor and goal, and these relations can become more difficult to manage as the computer task becomes more complex.

Navigating Alley Mazes

A two-dimensional maze with multiple T-intersections presents a sequence of binary spatial decision points. One can conceive of each choice point as presenting two (potentially conflicting) opportunities: (a) to move toward the goal according to Euclidean space and (b) to move toward a path that continues. These two properties of the choice point are orthogonal; the path that leads directionally toward the goal may or may not continue, and the path that continues may or may not lead immediately in the direction toward the goal. Relying on the single Euclidean relation between cursor and goal in navigating these mazes will lead to predictable errors at choice points where the correct path leads away from the goal. Once moving along a path, consideration of continuation (i.e., looking ahead to see if the path continued) would lead to correction of errors before striking the end of the alley. Alternatively, if the actor pays no attention to continuation, it would move the cursor directly into the wall at the end of the alley.

Fragaszy, Johnson-Pynn, Hirsh, and Brakke (2003) presented three capuchins with 192 mazes, each maze only once, on a computer screen. The monkeys used a joystick to move a cursor through the mazes to a marked

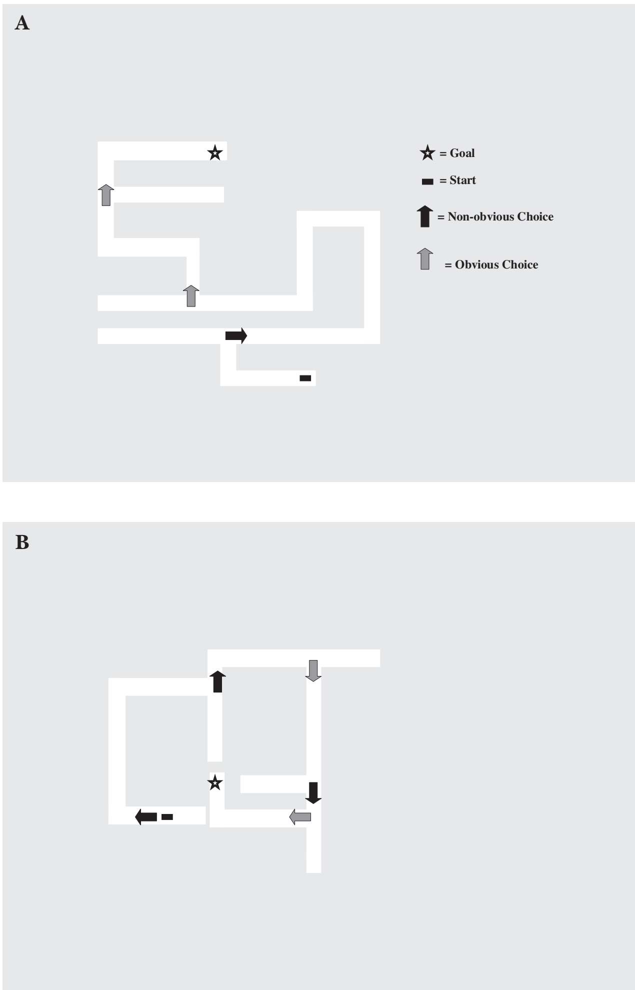

Figure 2: Two Sample Mazes Presented to Capuchin Monkeys and Chimpanzees.
NOTE: The actor used a joystick to move a cursor (not illustrated in the figure) through the alleys of the maze to a goal region (denoted by the star) on a computer monitor. Arrows indicate choice points; black arrows indicate choice points in which the incorrect choice appears to lead more directly to the goal than the correct one (a nonobvious choice). The first maze (A) contains three choice-points, one of which is a nonobvious choice. The second maze (B) contains five choice-points, three of which are nonobvious choice points. Capuchin monkeys and chimpanzees solve mazes like those shown here, although they make errors while doing so. (Drawings by Julie Johnson-Pynn and Sarah Cummins-Sebree).
SOURCE: Fragaszy, Johnson-Pynn, Hirsh, & Brakke (2003).

end point to receive a food treat. The mazes each contained from one to five binary choice points, and zero to three of the choice points required selecting a nonobvious choice (such as the path leading away from the goal) as the correct path. Two representative mazes are illustrated in Figure 2. We presented the mazes in what we considered an ascending order of difficulty, from few to many choices and from few to many nonobvious choices. The most difficult mazes, presented last, each contained five choice points, of which three presented nonobvious choices. Since completing this study, we have presented the same mazes, in random order, to an additional four capuchins (Hoy, 2004; Hoy & Fragaszy, unpublished data).

All seven capuchin monkeys strongly preferred to move in the Euclidean direction of the goal when reaching a choice point. Counting only the initial decision at each choice point, the error rate was 61% where the correct path led 60° or more away from the goal (nonobvious choices) compared to 34% at other choice points. The monkeys managed to complete virtually all the mazes, however, even those with several turns away from goal, through sheer persistence. Their difficulties with the nonobvious choices might indicate that they did not integrate the two orthogonal spatial relations of Euclidean direction and path continuation into their action. Alternatively, they might have been unable to inhibit moving the cursor directly toward the goal or not weighed the cost of an error as significant, even if they recognized that a path going in the "right direction" might not continue.

One finding suggests that the monkeys sometimes looked ahead at least a short distance as they moved the cursor: they self-corrected the cursor's direction of travel after making an error before they moved the cursor to the end of the alley (range = 17%-51% of errors). This finding, coupled with the monkeys' predilection to move directly toward the goal, suggests that they managed the two spatial relations in this task sequentially. First they moved the cursor toward the goal, then they looked ahead to see if the path continued. Their performance indicates, as predicted by our model, that managing concurrent spatial relations is more challenging than is monitoring a series of single spatial relations in sequence.

The continuing work with the monkeys solving these mazes evaluates the stability of the monkeys' strong bias to move directly toward the goal (and conversely, their tendency to incorporate path continuity into their decisions about choice of path) as well as other indices of spatial reasoning (such as self-corrections after making an error). The picture emerging now is that, with practice, the monkeys choose the correct path at nonobvious choice points increasingly more often. Thus, they apparently can learn to monitor the two relations concurrently or, at the least, to inhibit movement directly toward the goal so that the second relevant spatial relation (continuity of the path) can be integrated into the decision. This is a challenging task for capuchins, but they can master it. Similarly, they can master reaching into reflected space, mastering an indirect relation between movement and vision.

Using Visual Information Under Altered Relations Between Vision and Location

Using a mirror to guide movement to a point in space alters the normal relation between vision and action to prehend an object. This task introduces one additional, indirect, specific spatial relation to the problem of visually guided reaching. The actor must reach, not at the image in the reflection, but into the space reflected in the mirror and to a specific point in that space. Capuchins can master this problem (Marchal & Anderson, 1993). When honey-dipped raisins (a truly decadent delight for capuchin monkeys) were stuck onto a surface below the front edge of the monkeys' cage (and thus out of their view), two monkeys out of three learned to locate them efficiently with their hands when they could look in the mirror but searched randomly when they saw only the nonreflective side of the mirror. One monkey became so proficient that he got the raisin in a single reach per trial after the eighth session with this task, compared to two to six attempts per raisin without the mirror.

To summarize, when acting spontaneously with multiple objects, seriating multiple nesting cups, navigating two-dimensional displays using a joystick, and using a mirror image to guide reaching, capuchin monkeys rely initially and sometimes persistently on a single relation or (as in the case of the nesting cups, for example) adopt strategies that permit them to reach the goal without reasoning about two relations concurrently. In navigating two-dimensional mazes, the monkeys may learn to look ahead to the end of an alley at a choice point rather than always to move into the path that goes most directly toward the goal, but they have alternative strategies that can get them through this problem as well (such as making a random choice, then reversing if the path ends). Work with this experimental paradigm is continuing, so we will learn more about how they organize their actions in these mazes.

Overall, capuchin monkeys usually act spontaneously with objects to produce single indirect relations (e.g., between an object and a surface). However, the monkeys have mastered more complicated actions such as using a joystick to control a cursor, a task that integrates two indirect relations and has other complicating features, including a disjunctive spatial relation between joystick and cursor and a translation from 3-dimensional to 2-dimensional movement in that relation. They can also handle multiple relations sequentially (as in the nesting cups problem).

Can the same strategies suffice to use an object as a tool? Or does using an object as a tool inherently involve management of additional or different spatial relations? We turn to this subject next.

APPLICATION OF THE RELATIONAL SPATIAL REASONING MODEL TO USING TOOLS BY CAPUCHINS

An animal uses a tool, according to the well-accepted operational definition proposed by Beck (1980), when it uses an object as a functional extension of its body to act on another object or a surface to attain an immediate goal. Working from the relational perspective, we include a conceptual element in the definition: an individual uses a tool only when the individual produces a spatial relation between the tool and another object or surface, rather than simply uses an already existing relation. This addition excludes some situations that others commonly include as examples of tool use, such as pulling in a stick already in contact with a target (say, a piece of food) when the actor arrives on the scene. In our scheme, the actor has to place the stick in relation to the food to use the stick as a tool. Adding this feature to the definition increases the cognitive significance of using a tool; it means that the tool user has considered alternative actions and selected a specific one, and thus that it has reasoned a solution to the problem, according to Bermudez (2003). Using this definition, a recent survey turned up 50 studies reporting tool use by captive capuchin monkeys between 1980 and 2003 (Fragaszy, Visalberghi, et al., 2004). These studies have included a wide variety of situations and methodologies. Trying to evaluate the shared features of these reports, and to compare them to equally varied reports about tool use in other species, is what sparked our interest in developing the relational properties model presented in this review.

How shall we consider the kind of reasoning that accompanies using a tool? Greenfield (1991) and Matsuzawa (1996, 2001) conceptualized the cognitive aspects of tool use as following from the sequentially nested property of spatial relations embodied in tool use. Matsuzawa's model (what he calls the "tree model") is shown in Figure 3 as a useful example of this general idea. In this model, the objects participating in the action are specified, and the order in which each spatial relation is produced is indicated: a direct action on an object (eating a termite) is listed as Level 0; in Level 1, an object is used in some way as an intermediary between the body and the goal object (using a twig to fish for termites). In Level 2, using the example of nut cracking, the nut and the anvil stone are connected at one node, and the hammer stone is connected to these (joined) elements. Thus, the temporal sequence of producing the spatial relations is reflected in the branching patterns; later actions are shown as higher nodes. Any particular combination can be repeated, using what Matsuzawa (1996) calls an embedding rule. As he noted, a sequential behavior following an embedding rule can have an

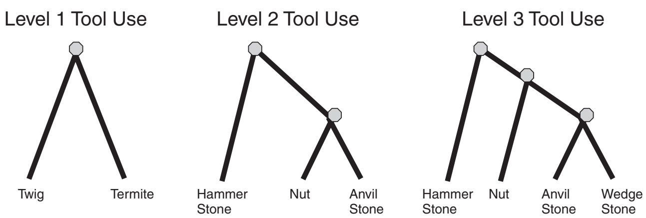

Figure 3: Matsuzawa's (2001) Hierarchy of Tool Use Using the Tree-Structure Analysis.

NOTE: According to our relational model, the example of Level 1 tool use given in the tree structure model (using a twig to collect termites) is a static, direct action producing one spatial relation. The relational model specifies the example of Level 2 tool use (hammering a nut with a stone placed on an anvil) as a sequence of two actions that produce a static relation with respect to the nut and anvil stone, followed by a dynamic relation between the hammer stone and nut. The example of Level 3 tool use is described in our relational model as production of a direct, static relation between the anvil stone and wedge stone, followed by a concurrent, two-relation action that requires (a) a direct, static relation between the nut and the anvil stone and (b) a direct, dynamic relation between the nut and the hammer stone. Thus, there are three relations in this example, two of which are concurrent, one of which is dynamic, and all three of which are direct.

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infinite number of nodes in the tree, and the complexity of the resulting tree structure is indicated by the depth (number) of nodes. Figure 3 includes as Level 3 the form of tool use he observed that incorporated the most sequential relations, wherein chimpanzees used a wedge stone to shim a wobbly anvil stone, then placed a nut on the anvil, and finally cracked the nut with a hammer stone. Greenfield's (1991) "action grammar" model of increasing hierarchical complexity in the development of manual action and language is similar in structure.

The sequential hierarchical models of Greenfield (1991) and Matsuzawa (2001) delineate two important features of the actions in tool use: the number of spatial relations produced by the actor and the order in which they occur. In this respect, they are presented by their authors as embodying shared properties with language, and Matsuzawa also suggests the value of this model in analyzing social relationships; this generality is an important feature of such models. More relevant for the topic of this review, they provide a principled basis to evaluate different forms of tool use (such as cracking nuts, fishing for termites, or using a stick to lever open a fruit). However, neither sequential hierarchical model addresses several other aspects of the spatial relations embodied in using a tool that, from the perspective of ecological theory (E. J. Gibson & Pick, 2000; J. J. Gibson, 1979; Lockman, 2000), have an impact on the problem in a substantive way. These models do not consider the specificity of the spatial or force relations the actor must produce, nor the temporal flow of the activity, such as the modulation of activity when objects and surfaces move during the course of using the tool. From an ecological perspective, one must consider how the process of using a tool unfolds in time and in space, through actions performed by the body and in accord with the physical context of action (e.g., the nature of the objects used and the supporting surfaces); that is, with due consideration to the properties of spatial relations mentioned in Table 1.

Below, we examine selected recent studies of tool use in capuchin monkeys with respect to the five properties of spatial relations listed in Table 1. The studies are organized by the superficial structure of the problem (use a stick to probe or push; use a stick to pull; use a stone to pound; see Table 2). Our review makes clear that tasks with equivalent numbers of spatial relations can vary in other properties relevant to cognitive demands and that considering these other properties enhances our understanding of the monkeys' behavior.

Using Sticks to Push and Probe

Many studies have investigated capuchins' ability to use a stick to probe or dip for food or to insert a stick into a tube to push food out. In the dipping/probing task, a container is filled with a viscous food (e.g., syrup, apple sauce, yogurt) that can be retrieved through openings too small for a capuchin's hand. The apparatus is fixed to a rigid surface or placed on the ground, and the monkey uses sticks or other long, thin objects to probe into the container. Inserting a stick into an opening to probe for a viscous material requires producing a single, static, permissive relation. In other words, this is a simple tool-using task. Capuchins can master this task even before their first birthday (Westergaard & Fragaszy, 1987; Westergaard, Lundquist, Haynie, Kuhn, & Suomi, 1998).

Using a stick (or hoe or cane) to move an object across a surface by pushing it with the stick can be more complicated. We have no experimental data on capuchins given the problem of pushing an object across a smooth, open surface. We do, however, have a provocative set of data about capuchins pushing a piece of food out of a tube using a stick as a probe, presented to capuchins by Visalberghi and Trinca (1989) and Visalberghi and Limongelli (1994) and to additional monkeys and apes by Visalberghi, Fragaszy, and Savage-Rumbaugh (1995). Pushing the food involves inserting the stick into the tube (one relation, indirect, nonspecific, static) and then pushing the food through the tube (second relation, sequential, indirect, nonspecific unless the food is small and the tube wide, for example; dynamic, because the action of pushing must be maintained over some period as the food moves out of the tube). This task is readily mastered by capuchin monkeys in laboratory settings. Introducing an irregularity in the surface (a trap in the middle of the tube so that the food falls into the trap if pushed toward it) introduces a third relation to the problem. Now the actor must also monitor the spatial relation between the food and the hole concurrently with monitoring the second relation, between food and stick. The third relation is concurrent with the second, dynamic, indirect, and nonspecific in the sense that the food will fall into the trap no matter where along the edge of the trap it moves. This variation of the task was beyond the mastery of three of the four capuchins that encountered it in Visalberghi and Limongelli's (1994) study. The fourth monkey became proficient at inserting the stick on the side that permitted her to avoid the trap while pushing out the food, but the monkey did not use the indirect relation that she produced between food and trap to do this. Instead, she discovered a different spatial relation that allowed her to avoid the trap: she learned to insert the stick into the end of the tube farther from the food, and in this way, she always avoided pushing the food into the trap in the middle. She may have been evaluating the relation between the food and herself (a direct relation) or between the food and the end of the tube (an indirect relation)—the outcome would have been the same. In any case, the monkey evaluated a single static relation before or outside of acting with the stick on the food, an effective strategy so long as the trap remained in the middle of the tube. It was not effective, however, when the trap was placed off-center in the tube, and the monkey never mastered this variation of the task.

Using Sticks and Shaped Sticks (Hoes, Canes) to Pull

Researchers have given nonhuman primates of several species a stick or shaped stick (hoe, cane, rake; hereafter all referred to as *stick*) to pull an object within reach (chimpanzees: Povinelli, 2000; Tomasello, Davis-Dasilva, Camak, & Bard, 1987; orangutans: Call & Tomasello, 1994; tamarins: Hauser, 1997; baboons: Westergaard, 1992; lion-tailed macaques: Westergaard, 1988). This action has also appeared spontaneously in many species (long-tailed macaques: Zuberbühler, Gygax, Harley, & Kummer, 1996; baboons: Beck, 1973; Tonkean macaques: Ueno & Fujita, 1998). Capuchins master using sticks to sweep in objects (adults: Cummins-Sebree & Fragaszy, 2005; Fujita, Kuroshima, & Asai, 2003; infants: Parker & Potì, 1990). In its simplest presentation, using a stick to bring something within reach does not require that the actor produce any spatial relation between two objects at all. When the stick is already in contact with the goal object or placed so that it can be pulled directly to the actor without regard for the position of the goal object (because both are contained within a channel, for example as in the tasks presented to chimpanzees by Povinelli, 2000), then the actor is using a direct relation to pull in the stick toward its body, and therefore the action does not qualify as tool use. This would be equivalent, in relational terms, to withdrawing a preplaced stick from a container of honey. However, when the actor must produce and/or monitor at least one indirect spatial relation to do so, using a stick to pull an object within reach is using the stick as a tool, as is inserting a stick into a container of honey, then withdrawing it, coated with honey.

The first spatial relation to manage in this problem is the position of the stick with respect to the goal object to be pulled toward the actor. Making contact between the stick and a discrete goal object (e.g., a small piece of food) requires producing a static, specific spatial relation. Visually guided placement of a stick to achieve a specific spatial relation to another object initially challenges capuchin monkeys. Monkeys observed by Cummins (1999) used a hoe (18 cm long) to pull in food when it was first presented (with the food in the center of the tray, directly in front of them, and the hoe positioned nearby, so that they needed merely to move it a few centimeters to left or right and then pull). Thus, they recognized from the outset what spatial relation they should produce. However, when the position of the food on the tray was altered, the monkeys would sweep the hoe far beyond or short of the food. These errors diminished with practice, and eventually the monkeys could maneuver the hoe to contact food at any position on the tray.

To retrieve the goal object effectively, the spatial relation between stick and the goal object must be maintained as the object is pulled toward the actor. Depending on the shape, size, and position of the tool, the location and properties of the goal object, and the properties of the surface across which the object is pulled, this may not require monitoring by the actor (as when the tool is large, the goal object small, smooth, and directly in front of the actor, and the surface over which it is pulled smooth, rigid, and flat). In this case, the task requires a static relation (the first positioning of the tool), and then the pulling action can proceed without monitoring the position of the goal object. On the other hand, many variations of tool, goal object, and surface can produce irregular or unpredictable movement of the goal object during the pulling process, and the actor will have to monitor the movement of the food with respect to the tool (a dynamic relation). Thus, to increase the difficulty of this problem, one could alter the situation in any manner that introduced a dynamic element into the spatial relation between the stick and the goal object. This could be done, for example, by using a goal object that rolled irregularly, and thus away from the tool. We are not aware of any study that has examined this possibility in a systematic fashion, but in

Figure 4: Xenon Chooses a Platform Containing a Barrier From Which to Retrieve the Food (A) and a Platform With a Smooth, Continuous Surface From Which to Retrieve a Treat With a Hoe Tool (B).

NOTE: We classify the action in the top photograph as a two-relation, concurrent, dynamic action that is direct with respect to the hoe and the food and indirect with respect to the barrier and the food. That is, the actor manages the relation between the food and the hoe by acting directly on the hoe; it manages the relation between the food and the barrier indirectly, by acting on the hoe. We classify the action in the bottom photograph as producing a single dynamic, direct relation (hoe to food) with no temporal properties. (Photos by Sarah Cummins-Sebree.)

our studies (see below) in which the monkeys used a hoe to pull in a piece of dried cereal or a raisin, these objects frequently slid sideways and out of contact with the tool, requiring the monkey to reposition the tool to make contact with the goal object again. Thus, this spatial relation is often dynamic.

Another way to increase the difficulty of the pull-in problem is to add an additional concurrent relation. Cummins (1999) did this by introducing an irregularity in the surface across which the monkeys pulled an object with a hoe (see Figure 4). She used two kinds of irregularities: a hole (3 × 10 cm) and a solid vertical barrier (4 × 10 × 4 cm). With an irregularity in the surface across which the monkeys had to pull the food, the task required monitoring the relation of food to tool (a direct, potentially dynamic relation) and the relation between food and the surface irregularity (a concurrent, indirect, permissive, dynamic relation). The relation between the goal object and the surface irregularity is intrinsically dynamic because the goal object moves with respect to the irregularity. This version of the problem thus presents two concurrent relations, at least one of which is dynamic and often both are being dynamic. The monkeys managed to move the food past the barrier (9 times out of 10 trials) in the first 10 trials (two subjects) and after 40 trials (one subject). Two monkeys reached the same level of competence at moving food past the hole in 68 trials and 126 trials, respectively. The last monkey did not reach the criterion of success in moving the food past the hole. Thus, controlling the position of the food with respect to the hole seems more difficult than does controlling the food with respect to the barrier. The barrier, even though it impeded vision and movement of the food, permitted repeated attempts. The hole, on the other hand, afforded no repetition; the food was lost once it fell into the hole. But the important point for our discussion here is that with both kinds of surface irregularities, the monkeys mastered the indirect, concurrent, dynamic problem of moving the food with respect to the irregularity.

Cummins-Sebree and Fragaszy (2005) assessed another dimension of spatial management in pulling tasks by presenting variously shaped objects to the monkeys in different positions on the tray. In this case, the monkeys frequently rotated and turned the objects to achieve a specific spatial relation between a part of the tool object and the goal object. In the simplest version of the problem, six monkeys were presented over successive trials with a pair of canes, each with a piece of food near the hook of the cane. The monkeys could choose one of the canes to pull in one piece of food. When the food was positioned outside the curve of one cane and within the curve of the other identical cane, capuchins tended to choose the one containing the food within the curve (80% of trials for this pairing type). Thus, they recognized the importance of the position of the food with respect to the curve of the cane, and they selected the cane that required no action on their part to produce a spatial relation between food and cane. Similarly, when they had a choice between an object of other shapes already positioned appropriately (so that it just required pulling in), they preferred that object to another that they had to reposition before pulling. In this respect, they were similar to tamarin monkeys that also preferred canes and other objects that allowed them to pull in food without producing a spatial relation themselves (Hauser, 1997). This task does not meet our definition of tool use because the actor did not produce any spatial relation between one object and another; it merely used a preexisting relation. However, the capuchins also managed the first-order version of the cane problem, in which they actively produced an appropriate spatial relation between tool and food by rotating and repositioning the tool; the tamarins did not. Capuchins were not always successful at repositioning the tool; indeed, each monkey made 4 to 10 attempts to reposition a tool before succeeding to use it to pull in the food, and across all testing, they succeeded on 20% to 46% of the trials in which they repositioned the tool.

In this task, the capuchins must occasionally reposition the tool to produce effective contact between the tool and food; in all cases they must maintain that contact so as to retrieve the food. Thus, this task incorporates multiple elements of our spatial-reasoning scheme. This is also a dynamic task that requires indirect contact with the food (through the use of the tool), and depending on the contours of the tool, it may involve a specific or nonspecifc relation (specific if the surface area used to make contact with the food is at a minimum; nonspecific if the surface area is at a maximum). Producing a specific spatial relation is not an easy task for capuchins in such a demanding tool-using situation.

To summarize the monkeys' use of stick tools, the tasks presented to capuchin monkeys have incorporated one or two indirect relations, and in the two-relation problems where a surface irregularity had to be monitored, the second (concurrent) relation was dynamic. All of these conditions were mastered by some of the monkeys, indicating that concurrent dynamic spatial relations are not an insuperable challenge for them. The monkeys repositioned tool objects to bring them into contact with a goal object and, significantly, to alter the orientation of parts of the tool to the goal object (thus producing a specific spatial relation between tool and goal object). However, in all these problems, precise control of the distal end of a long tool is a challenge for them. The biomechanical properties of the tools that were provided (e.g., their relatively long length with respect to the monkeys' arms and perhaps their mass and other properties, such as inertial tensor—Wagman & Carello, 2001) and the constraints of manipulating them through bars or apertures no doubt contributed to the monkeys' difficulties. We do not yet have a good measure of the monkeys' aptitude for precise placement or modulation of movement with a tool object; this topic is ripe for further investigation. The coordinative demands of skilled movement with an object are an integral part of the cognitive package used in tool use (Bernstein, 1996; Berthoz, 2000; Turvey, 1996).

Using One Object to Break Another

Cracking open a nut (or any husked fruit or a shell; we shall use the generic label *nut* for all such foods) can require producing one or more spatial relations, and these relations can vary in all the properties listed in Table 1. In the simplest circumstance, as in probing, the task involves producing a single spatial relation between a held object and a static target, as when the nut is firmly attached to a substrate. Striking the nut with the tool object (*hammer*) is a static relational act. When the nut is placed on a specific surface (hereafter, *anvil*) by the monkey and then struck, the problem embodies two static relations (nut to substrate and hammer to nut). When the monkey places the nut on an anvil and then pounds it with the hammer (a second relation), meanwhile monitoring that the nut stays on the anvil as it is struck, the task has two concurrent relations, one of which is dynamic. Whereas to date all the studies of nut cracking in captive situations fall into the category of single-relation problems, those in more natural settings include two relations. We will focus our attention on studies concerning dynamic single- and dual-relation problems.

Using a Stone to Crack Nuts

A nut-cracking sequence typically consists of a capuchin picking up a nut and carrying it to a stone or other loose, hard object, placing the nut on the ground beside the stone, then lifting the stone with one or both hands and bringing it down on the nut. When naïve capuchins encounter nuts together with other hard objects, they combine the objects and nuts in all possible combinations of actions and spatial orientations (e.g., holding the nut in the mouth while pounding the other object on the floor or placing the nut on top of the other object and pounding both of them—in that spatial configuration—on the floor) (Visalberghi, 1987). Occasionally, the monkey first places the nut on the ground and pounds it with the other object. The occurrence of this effective combinatorial action becomes more frequent with time (see also Anderson, 1990). Researchers have seen individuals as young as 2 years old use a hard object to crack open loose nuts (Anderson, 1990; Resende, Izar, & Ottoni, 2003).

Very recently, Fragaszy, Izar, et al. (2004) documented a population of wild capuchins in Piauí, Brazil, using stones to pound open nuts placed on an anvil stone with stone hammers. This is an important discovery, as it is the first documentation of routine tool use (i.e., by most individuals in a population, over a long period) by wild capuchins. Moreover, the form of the activity is exactly

Figure 5: A Wild Capuchin Monkey (*Cebus libidinosus*) Cracking a Palm Nut With a Stone, Using an Anvil.
NOTE: The recent discovery that populations of wild capuchin monkeys use stone tools and anvils opens up new opportunities for study of relational actions in natural settings in this genus (see Fragaszy et al., 2004, for further information). (Photo by T. Falotico.)

that noted for wild chimpanzees in some parts of western Africa (Boesch & Boesch-Achermann, 2000; Inoue-Nakamura & Matsuzawa, 1997) that Matsuzawa (2001) has so elegantly diagrammed. The monkeys, like the apes, transport nuts to the site where they will be cracked, and they transport (then or at a previous time) a stone, large enough to crack nuts, to the site. The anvil surfaces used by capuchins are large in *situ* boulders, exposed rock, or fallen logs. The cracking activity begins with the production of one static relation (placing the nut on the anvil stone), which is quite specific, as the monkeys place the nut repeatedly in different places on the anvil, apparently until it rests without rolling in one of the small depressions on the anvil's surface that develop from the pounding activity. Then, the monkey strikes the nut with a heavy hammer stone (average mass = 1.1 kg; Visalberghi, Fragaszy, Izar, and Ottoni, unpublished data), producing a sequential, static, nonspecific, relation between hammer stone and nut. Capuchins living in semifree conditions crack nuts in a similar manner using hammer stones and anvil surfaces (Ottoni & Mannu, 2001). The monkeys studied by Ottoni and Mannu cracked much smaller palm nuts than did the wild monkeys observed by Fragaszy, Izar, et al. (2004) and used correspondingly smaller hammer stones, but the structure of the activity in terms of the nature and sequence of spatial relations produced by the monkey is the same (see Figure 5).

Cracking a nut with a hard object involves, at minimum, producing one static, nonspecific relation between tool and nut. But many features of the situation can increase the number of relations and the nature of each relation. For example, if the nut is loose and prone to roll when struck, and large enough, or if the hard surface is sloping or uneven, the actor may hold the nut during striking (managing a dynamic relation between nut and hard surface) if the shape and weight of the hammer stone permits the monkey to hold it in one hand. If it does not, the monkey may try to place the nut in as stable a position as possible, and this seems to be the favored solution of the wild monkeys in Piauí that are handling very large stones to crack large nuts. Further details of how the monkeys in Piauí manage to produce aimed strikes with the very heavy stones that they use to crack palm nuts will be forthcoming as systematic study of this interesting phenomenon gets underway.

APPLICATION OF THE RELATIONAL SPATIAL MODEL TO VIEWED EVENTS BY CAPUCHINS

We move now to spatial reasoning about viewed events, in which the actor anticipates the location of some object following movements through a space. These studies typically involve a passive viewer watching a display and indicating through an instrumental response where he or she anticipates an object can be found at the conclusion of the event (e.g., Berthier, DeBlois, Poirier, Novak, & Clifton, 2000; Hood, Carey, & Prasada, 2000; Hood, Cole-Davies, & Dias, 2003; Keen, Carrioc, Sylvia, & Berthier, 2003; Mash, Keen, & Berthier, 2003).

Predicting the Trajectory of a Moving Object

Do capuchin monkeys anticipate that objects moving in a straight line continue to move in a straight line unless other forces intervene, that solid objects block the passage of other solid objects, and that objects fall if they are unsupported? According to Bermudez (2003) and Spelke and colleagues (1992), these are canonical object properties that underlie human cognition; therefore, it is worth determining if other species know the world in the same way. The spatial relational model illuminates features of these events that might challenge the viewer's spatial reasoning.

According to our model, continuation of movement in a straight line involves a single dynamic spatial relation between object and surface. The impediment to movement provided by a solid barrier adds a second (static, sequential) spatial relation to the movement event (as the object comes to a halt when it reaches the barrier). Finally, the passage of the object over a gap in the supporting surface provides a second (dynamic, sequential) relation to the event (as the object falls when it reaches the gap). In this last instance, movement shifts from the horizontal plane to the vertical plane.

Fragaszy and Cummins-Sebree (unpublished data) examined these three elements of knowledge about object movement in capuchin monkeys using a "search" task, similar to tasks used by developmental psychologists to study young children's spatial cognition (e.g., Berthier et al., 2000; Hood et al., 2000, 2003; Keen et al., 2003; Mash et al., 2003). We presented a "puppet" display of a metal ball rolling across various surfaces to seven adult male tufted capuchin monkeys (see Figure 6). First, the monkeys learned that retrieving a metal ball and returning it to the experimenter produced a food treat. They could retrieve the ball after it rolled to a stop at one of several designated locations (windows cut into the clear acrylic panel covering the front of the display). Subsequently, they learned that they needed only to indicate the window where the ball would stop rolling rather than actually to retrieve the ball. At this point, their behavior indicated where they expected a rolling ball to come to rest. The experimenters then presented a series of displays to them where the ball moved in front of them but then stopped short of a learned "end" location. After they indicated their expectation for the window where the ball would come to rest, the ball continued on a linear path to its (physically logical) end point. A correct choice earned the monkey a food treat. Essentially, the experimenters asked the monkeys to predict where an object that they saw moving across a particular substrate would come to rest. This task is logically similar to the search tasks used with young children, in which the child views a ball rolling along a track with and without various obstructions and with or without transparent or opaque occluding panels between the child and the track. After viewing the ball moving along the track, the child is asked to retrieve the ball. The child's first search location is taken to indicate where the child expects the ball to have come to rest (e.g., Berthier et al., 2000; Hood et al., 2000, 2003; Keen et al., 2003; Mash et al., 2003).

After the monkeys became proficient with a few familiar layouts of horizontal surfaces and paths of movement, we conducted experimental sessions in which novel layouts were inserted among the familiar (training) layouts. We asked the monkeys to predict the ball's resting point in three situations. In Experiment 1, the ball rolled in a linear path across a continuous, unobstructed horizontal surface (the continuity experiment, panel d in Figure 6). In Experiment 2, there were two potential end points where the ball could travel when a solid vertical barrier appeared along the horizontal path (the solidity experiment, panel b in Figure 6). In Experiments 3 and 4, the ball traveled along a horizontal surface; novel trials presented the horizontal surface with a gap along its length that was twice the diameter of the ball (the gravity experiments, panels a and c in Figure 6). Experiments 3 and 4 differed in the location of the ball at the time of choice (near the gap in Experiment 3; at the center of the panel in Experiment 4). In all the experiments, the ball appeared to the monkeys to move autonomously, although in fact the experimenters controlled its motion from behind a thin wood-fiber panel by means of a strong magnet that they moved in the desired manner. Each monkey completed 12 to 18 trials with novel layouts in each type of task, as well as 24 to 54 familiar layouts. The familiar layouts and a sample of the novel layouts used in each experiment are illustrated in Figure 6. The monkeys maintained nearly perfect performance on the familiar layouts during the test sessions, so we discuss here only their performance on the trials in which the monkeys encountered novel layouts.

Capuchins chose the correct (physically possible) end points of the ball's path in Experiment 1 significantly more often than expected by chance (52% correct vs. 33% expected by chance). Thus, they were moderately accurate in predicting that a ball rolling in a novel linear trajectory across an unobstructed surface would continue on that linear trajectory. The monkeys were consistent in their performance over the three blocks of trials with novel layouts (6 novel trials per block). In Experiment 2, as in Experiment 1, the monkeys chose the correct window significantly more often than expected by chance (on 63% of trials vs. 50% expected by chance), and also as in Experiment 1, their performance was consistent across three blocks of trials with novel layouts. They thus moderately accurately predicted that a ball would roll to the unobstructed side of the path. However, the monkeys had much less success at anticipating the path of movement of a ball along a surface with a gap, the layout in Experiments 3 and 4. Indeed, in Experiment 3, where the ball paused just in front of the gap (and close to an end point that was "possible" during training trials), the monkeys selected the *incorrect* end point 62 times out of 70 trials. We reasoned that the procedure may have biased the monkeys' preference for an incorrect window, so in Experiment 4, we altered the trial-initiation procedure so that the ball stopped moving (signaling the monkey to make a choice) at the center of the path, equidistant between the two sides of the apparatus with the windows, to signal that the monkey could make its choice. In this circumstance, all of the monkeys failed to choose a correct window at levels significantly greater than chance, although they did not, as in Experiment 3, choose the incorrect window more often than others.

These studies suggest that the monkeys are able to predict some aspects of an object's movement. They are not uniformly proficient, however. They coped better with a single relation in one plane of movement (linear continuation or a solid barrier stopping travel) than with the double relation of an object rolling toward a hole and falling downward (where linear continuation is fol-

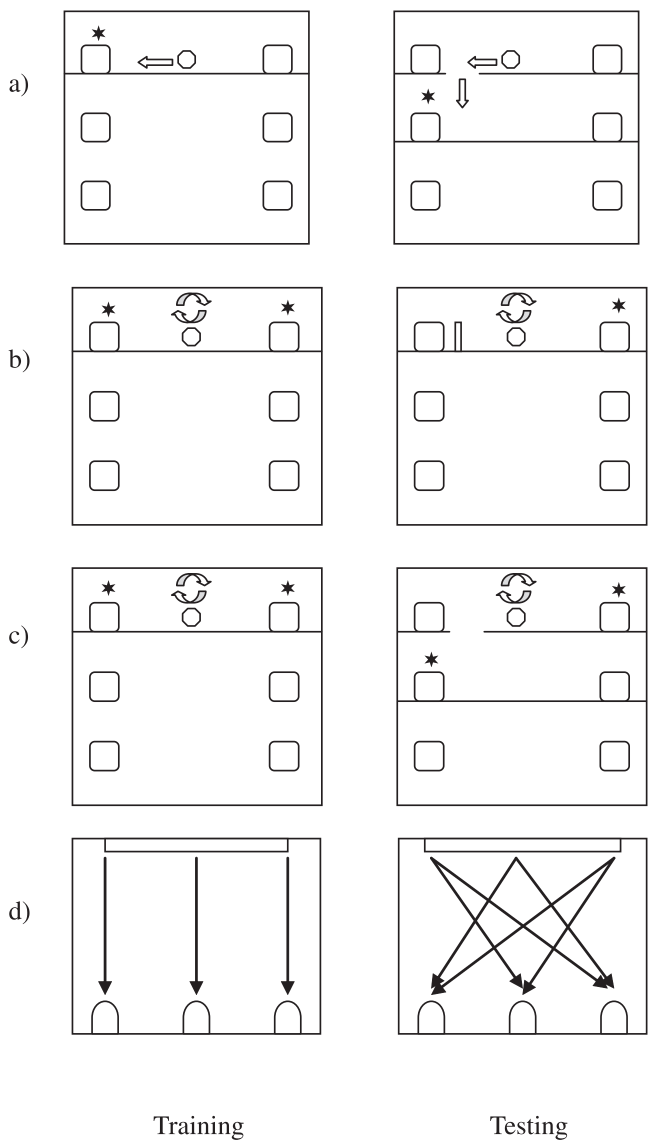

Figure 6: Experimental Arrangements Used to Evaluate Capuchin Monkeys' Ability to Predict the Future Position of a Rolling Ball.

NOTE: By placing its hand on the window, the monkey indicated the window (shown by an outline in the figure) where the ball would appear if it continued to move to the left or right along the shelf. For all of the diagrams, the arrows indicate the movement of the ball, and the asterisks indicate which choices were correct (and resulted in the monkey receiving a food treat):

(a) *Gravity experiment.* Training (left): Half of the time, the ball rolls toward the left window, the other half to the right window. The ball stopped rolling at a point about two thirds of the way toward one window. For any training trial, the correct (rewarded) choice was the left window when the ball moved to the left and the right window when the ball moved to the right. Testing (right): The ball first moved about two thirds of the way toward one window and then stopped (just before reaching a gap). Once the monkey chose a window, the ball was moved over the gap so that it fell to the next platform. On half the trials, the gap was toward the right window and the ball rolled to the right; on the other half, the gap was on the left and the ball rolled to the left.

(b) *Solidity experiment.* Training (left): The ball moved in a circle and came to rest in the center of the shelf; the monkey then chose a window. Choice of either window was rewarded. Testing (right): A barrier was present on one side of the shelf. The correct choice was the window opposite the barrier.

(c) *New gravity (conducted after the solidity experiment).* Training (left): The ball moved in a circle and came to rest in the center of the shelf; the monkey then chose a window. Either window was correct. Testing (right): A gap was present on one side of the shelf; the correct choice was either the window opposite the gap or immediately below the gap.

(d) *Continuity experiment.* Training (left): The ball rolled on a linear path toward the lower end of the tray. It stopped several centimeters above the windows. The monkey then chose one of the windows (indicated by outlines in the figure). Testing (right): The ball rolled along a novel (diagonal) path toward the lower end of the tray, stopping a few centimeters above the windows. Some monkeys became proficient at predicting the ball's future position in the solidity and continuity experiments, but all failed to master the gravity problems in both formats. (Drawings by Sarah Cummins-Sebree.)

lowed by a change in the plane of movement). Considering these events in terms of the nature and number of spatial relations governing object movement provides one explanation of why the monkeys' anticipatory performance varied across conditions. If the perceiver is attending to a single element in a situation where two or more elements jointly determine the outcome, then its predictions about what will happen under varying scenarios will inevitably be inaccurate. We see in this work that capuchins are likely to cue on one relation; learning to integrate two relations into problem solving requires experience. This mirrors what we have found about capuchins' proficiency at solving two-dimensional mazes, as reviewed earlier. It also matches what we know of young children learning to solve problems by moving objects in space (e.g., Klahr, 1994) and, indeed, learning to solve problems in various domains of activity (e.g., Case, 1992).

Tracking a Fixed Spatial Relation Through Rotational Transformation

Potì (2000) conducted an ingenious experiment to evaluate capuchin monkeys' relational reasoning about sets of objects. She presented capuchin monkeys with two identical boxes placed on a rotating tray (see Figure 7A). A black cylinder, visually distinctively different from the boxes, was closer to one box than the other, and thus served as a landmark, or allocentric cue of the identity of the boxes. After the monkeys saw the experimenter hide a food treat under one of the two boxes on the circular tray, a panel blocked their view, and the experimenter rotated the tray. In this way, the boxes moved in relation to the monkey's body and in relation to external cues (i.e., the room where she tested the monkeys). However, the boxes remained in a fixed spatial relation to the black cylinder on the tray and to each other. Then the experimenter raised the panel, and the monkey could choose to lift one box (and retrieve the food, if it made the correct choice). The monkeys initially relied on an egocentric frame of reference to choose a box (i.e., a

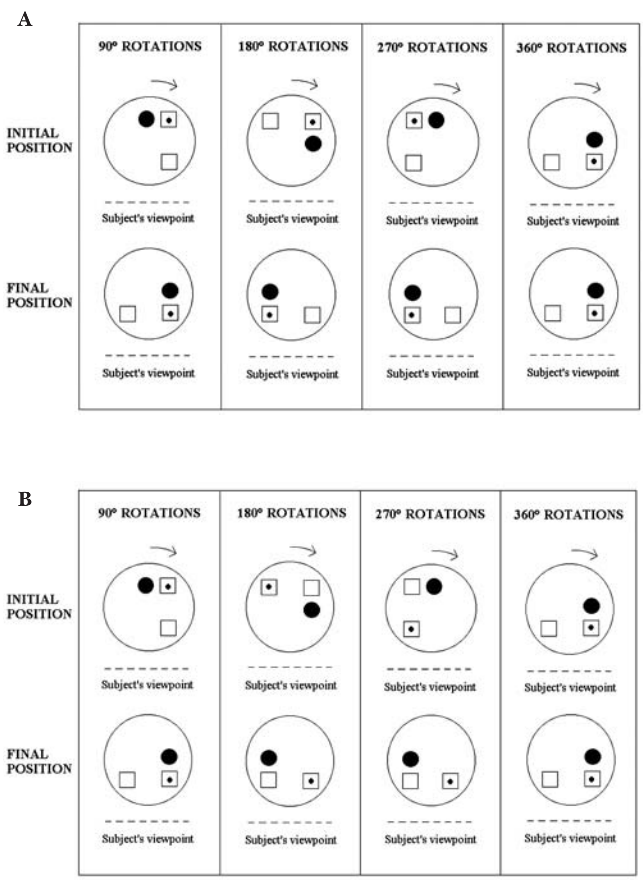

Figure 7: The Position of Objects on a Tray Used by Potì (2000) to Study Capuchin Monkeys' Abilities to Use Spatial Cues.

NOTE: The apparatus is depicted from above. The big circle indicates the tray, on which smaller objects were placed. A distinctive wooden block, shown as a filled black circle, was placed closer to one of two boxes, shown as squares. The box indicated by the square with the small black circle was baited. The dashed lines indicate the position of the monkey. At the beginning of each trial, a peanut was hidden in full view of the monkey (initial position). Then, the tray was rotated (in or out of the monkey's view) to the final position. (A) In Experiment 1, the monkey watched while the experimenter baited the container closer to the cylinder; then, a panel blocked the monkey's view while the tray rotated 90°, 180°, 270°, or 360°. (B) In Experiment 2, the experimenter randomly baited the container closer to, or farther from, the cylinder and then rotated the tray either behind a panel (as in Experiment 1) or in full view of the monkey. The monkeys reliably chose the baited container in Experiment 1 but had difficulty doing so in the Experiment 2 when they could not see the tray rotate.

SOURCE: Drawing courtesy of Patrizia Potì (2000, p. 71).

side bias), but they eventually learned to use the black cylinder as a landmark cue.

Potì (2000) then conducted a second experiment with new subjects. In the second experiment, the baited box alternated randomly between the closer and the farther position in relation to the cylinder landmark (see Figure 7B). Once again, the experimenter rotated the table after baiting the boxes. On one third of the trials, the monkeys could see the platform as it turned (as in Experiment 1); on the other two thirds of the trials, they could not see the platform turn. The monkeys preferentially selected the correct box when they could see the tray rotate and when the objects rotated out of view a full 360° (and thus reappeared at the original locations). This indicates that they could remember which box had been baited even though the box moved. However, they did not preferentially choose the correct box if the tray rotated less than 360° while they could not see it. Usually in these trials, they selected a box on the basis of an egocentric frame of reference (i.e., on their left side or their right side).

To summarize, in Experiment 1, the monkeys learned to choose the baited box that was the closer to the single landmark, regardless of whether the position of landmark and box had shifted (out of their view) with respect to the monkeys between the time of hiding and the time the monkeys made their choice. In this case, they could use a single allocentric spatial relation to guide their choice. In Experiment 2, they could choose the correct box when the correct box (of two possible) shifted across trials from close to or far from the landmark cylinder, but only when they could see the tray rotate or its position did not change (because it rotated 360°).

In both experiments, the boxes and cylinder were in a fixed (invariant) spatial relation among themselves (they did not move with respect to each other) on a given trial, and the whole layout moved with respect to the viewer and in the room coordinate system. This meant that the monkey had to track the relevant spatial relation through time; the relation was dynamic. According to our model of spatial reasoning, this is a more difficult problem than if the monkey merely had to remember the relational rule that the box closer to the cylinder was baited. But Experiment 2 presented an additional demand. Although the spatial relational structure of the task facing the monkeys in Experiments 1 and 2 was similar within a trial, the experiments differed in the constancy of the spatial relation between the baited box and the landmark cylinder. This relation was fixed in Experiment 1 and variable in Experiment 2. In Experiment 2, to choose the correct box required remembering the comparative linear distance of the two boxes to the cylinder (e.g., whether the baited box was closer to or farther from the landmark cylinder), despite the rotation of the entire frame (all three points). Remembering the current relation among internal elements while coping with a mobile transformation of the entire set of elements was too big a challenge for Potì's (2000) subjects. In the terms of our relational model, the variable spatial relation between cylinder and baited box added a second relation to the task. Although the second relation was not dynamic in a continuous sense, it was variable, and it therefore required additional monitoring compared to an invariant relation.

CONNECTING THE RELATIONAL SPATIAL MODEL TO CURRENT TOPICS IN COGNITION AND NEUROSCIENCE

Links to Neuroscience

Behavioral neuroscientists have been investigating the complexities of spatial problem solving in other venues. In particular, Maravita and Iriki (2004) discussed the neural correlates of the "body schema" in the activity of bimodal neurons in the premotor, parietal, and putaminal areas of the brain that respond to vision and somatosensory input from the hand or the arm. The "action space" of these bimodal neurons is centered on the body. However, action under altered spatial relations can change the action space of some of these neurons. In Japanese macaques (*Macaca fuscata*), the receptive fields of certain bimodal neurons are modified by the use of an object to extend the reach of the hand (a hoe tool). In short, the brain of a macaque learning to produce a spatial relation resets itself, so to speak, so that the entire space of action of the tool object (that extends reach) is included in the body schema. The tool becomes, neurally speaking, an extension of the body. In this sense, one might conclude that the macaque has managed to change the brain's treatment of the produced spatial relation from indirect to direct and thus to simplify the problem of managing its production. This matches the process we observed as capuchins mastered using a joystick to control a cursor, in which the monkeys eventually acted as though the hand directly controlled the cursor; by extension, it predicts that any skilled control of an indirect spatial relation (as for example between a prosthetic robotic hand, controlled by cortical activity alone, and a target—Helms-Tillery, Taylor, & Schwartz, 2003; Taylor, 2002) could involve a similar alteration of bimodal neurons relating to the body schema.

Macaques, unlike capuchins, only very rarely use objects as tools. Thus, it is no surprise that Japanese macaques studied by Ishibashi, Hihara, and Iriki (2000) needed hundreds of trials to master the problem of moving a hoe laterally to produce the necessary spatial relation between hoe and food so that they could sweep in a piece of food across a solid, smooth, horizontal surface. Ishibashi and colleagues' interest in the monkeys' actions with the tool was not the skill per se but in the associated alterations in activity patterns, neurotrophic factors, and gene expression in the forebrain that accompanied skill (Hihara, Obayashi, Tanaka, & Iriki, 2003; Ishibashi et al., 2002a, 2002b). When the macaques used two objects in sequence (one stick to push a food out of a tube and a second stick-hoe to pull the food within reach), prefrontal and parietal neural activation was detected (Obayashi et al., 2002). Maravita and Iriki (2004) mentioned that the monkeys quickly mastered the sequential task, unlike the slow mastery evident during learning to use the hoe tool in the first place. Maravita and Iriki noted that further study of neural correlates of learning to use tools in sequence will be valuable. We agree, and we point out that such work will also be of value in learning about neural plasticity associated with the management of multiple concurrent spatial relations. Systematic evaluation of the neural correlates of dynamic and multirelational problems, as laid out in our model, could be an interesting extension of this line of work. We wonder, for example, how the receptive fields of bimodal neurons are altered when a hinged tool is used (thus adding an additional relation to the tool that extends reach). Given their greater propensity to use objects as tools, inclusion of capuchins in imaging work of this type would be most interesting. However, they are not apt subjects for experimental procedures that require lengthy sessions in physical confinement (Fragaszy, personal observation), whereas macaques do participate well in such procedures.

Links to Physical Reasoning

Perceiving spatial orientations of objects at rest and movements of objects about axes or across planes is part of spatial reasoning. Indeed, understanding spatial orientation is a key aspect of physical reasoning in humans. Humans can reason accurately about the shapes, motions, and transformations of objects so long as they can form "useful descriptions" of component orientations to guide reasoning (Pani, 1997, 1999). A "useful description" is one in which the axes of the relevant objects and surfaces are accurately perceived, so that shape, motion, or translation can be expressed in relation to these axes. Adult humans tested by Pani (1997) appear to work from a general description of an object, with particular reliance on the vertical axis (e.g., slanted, parallel, tilted), to imagine how an object will appear after it has rotated. Pani (1997) noted that in a rotation problem the individual must locate the position and orientation of the given axis of rotation and then imagine the appropriate circular motion around it. This he describes as a "concrete procedure" that employs basic processes such as eye movements, attention, spatial organization, and working memory. These cognitive procedures are likely shared with other creatures that reason about space. We suggest that concepts of orientation presented by Pani (1997, 1999) can be useful in studying the cognitive aspects of producing spatial relations among independent objects in other species, as it has been in studying how humans imagine an object's rotation. For example, Potì (2005) mentioned the salience of the vertical dimension for chimpanzees' spontaneous constructions with multiple objects and their difficulty with repeating horizontal relations. In contrast to children, chimpanzees rarely place objects next to each other, although they routinely place one object inside another and one object on top of another, as we saw also in their behavior with nesting cups (Johnson-Pynn et al., 1999).

Pani (1997) noted that invariant (symmetrical) properties of physical structures lead to redundancy, and redundancy supports efficient encoding. Many important spatial properties of objects with respect to other objects or surfaces (e.g., parallel, perpendicular, vertical, same) are singular, meaning that they have a categorically unique value. It is not necessary to count the degrees in an angle to identify that two objects are perpendicular to each other (i.e., at 90°). When perceptions are organized in terms of singular spatial properties, spatial reasoning tends to be accurate and efficient, according to Pani (1997). If singular spatial relations support efficient perception, they are a logical starting point to study spatial reasoning and neural reorganization during learning to produce and use spatial relations. For example, we predict that problems involving one or more singular spatial relations will be easier to solve than problems involving less specified spatial relations.

Static and Dynamic Spatial Reasoning: Focus on Special Populations

Returning briefly to the issue of dynamic versus static relations and their relative demands on the perceiver, O'Hearn, Landau, and Hoffman (2005) reported that children with Williams Syndrome, a rare genetic disorder, have great difficulty, compared to age-matched normal children, in tracking multiple moving targets. They have no trouble remembering the location of multiple points or tracking the movement of a single object; their deficit seems peculiarly restricted to tracking independently moving points. Individuals with Williams Syndrome also display distinct impairment in certain visuospatial capabilities, namely, copying spatial models, either by drawing or making block constructions, but they are not impaired at recognizing biological motion, faces, or objects. O'Hearn et al. suggested that one possible explanation for the pattern of errors that Williams Syndrome children exhibit in tracking multiple points is that these children use fewer visual indexes (*sensu* Scholl & Pylyshyn, 1999), an hypothesized mechanism that specifically supports tracking multiple objects simultaneously, through continuous, simultaneous updating of multiple locations of discrete objects (or in two dimensions, points or contours). O'Hearn et al. suggested that the similar range of performance achieved by Williams Syndrome children at tracking multiple objects and at block construction tasks supports the interpretation that both of these tasks involve visual indexing, as Pylyshyn (2000) suggested. The distinction that Pylyshyn has highlighted between memory for static locations and ability to track moving objects over time corresponds to the distinction in our model between perceiving or producing a static spatial relation (between an object and a surrounding frame of reference) versus a dynamic relation.

The relational reasoning model we have put forward suggests that styles of reasoning about perceived motion would also apply to building with blocks. Constructing a stable form with multiple blocks requires aligning and positioning objects with respect to several coordinate systems and often also with respect to gravity. Moreover, our model predicts that people with limited ability to perceive or produce concurrent dynamic spatial relations would likely have difficulty managing to use tools where the problem embodied concurrent dynamic relations. Some evidence supports this suggestion. Limongelli (1995) reported that 3-year-old children, after just a few trials, could push a treat out of a trap tube (a transparent tube with a "trap" in the center of it; the same problem presented to capuchins by Visalberghi and Limongelli, 1994) without error, and they could explain before acting what would happen if they pushed with the stick from one side or the other. In our framework, this task contains three relations. The first (a), putting the stick into the tube, is indirect and static. The other two, pushing the food with the stick (b) while avoiding the trap (c), are indirect, dynamic, and concurrent (see Table 2). Children 27 months old, on the other hand, did not manage to solve this problem effectively (Visalberghi, 2000). Similarly, a child with Williams Syndrome presented with the trap-tube problem for 20 trials at 4 years 10 months always chose the same side of the tube, thus failing on half of the trials because the position of the food with respect to the trap was randomized. When given the task again 2 months later, after the experimenter explained to her what to do, she failed only once. However, she was not able to explain why she succeeded, although she had "very good verbal skills" (Limongelli, 1995).

CONCLUSIONS

The action-perception perspective emphasizes the actor's search for information and the significance of learning to perceive relevant features of the situation to guide future goal-directed action. This approach emphasizes knowledge as embodied in action and emphasizes the basis of learning to do any skilled action (including using objects as tools) in discovery through actions, perceptual learning, and practice in a particular context (Bernstein, 1996; E. J. Gibson & Pick, 2000; Smitsman, 1997). This perspective calls for an analysis of spatial problems in terms of how surfaces should be related to other surfaces, how the actor perceives the relation between its actions and the movement of objects, and how the actor uses the body to achieve the desired forces and positions of objects with respect to surfaces and to each other (E. J. Gibson & Pick, 2000; J. J. Gibson, 1979; Lockman, 2000). The action-perception perspective applies to problems involving prediction of movement of objects and instrumental actions with objects, as treated in this review, as well as to other types of spatial problems not treated here.

We have drawn on this perspective to develop the relational model of spacial reasoning laid out in this review. An important advantage of our model is that it provides an integrative explanation for behavior in situations that are currently treated as disparate. Specifically, our model links the organization of spontaneous behavior with objects in the course of exploratory activity or play, goal-directed actions with objects and in space in the course of solving a problem, and judgments about object movement in situations where the actor is not controlling the movement or position of objects. All these behaviors reflect, in our view, the actor's attention to or production of spatial relations having particular properties, as laid out in Tables 1 and 2.

Our model makes testable predictions about the difficulty of spatial tasks in accord with their relational properties, including critical temporal properties not addressed by other models (e.g., Greenfield, 1991; Matsuzawa, 2001). One prediction our model makes is that the temporal dimension of spatial relations powerfully affects the difficulty of the problem for the actor. Circumstances in which the individual must detect or produce dynamic relations are more challenging than circumstances in which static relations suffice. A second prediction is that concurrent relations are more difficult to master than sequential relations, and a related prediction is that mastery of a concurrent relation will proceed by sequential mastery of the component relations, then by their integration. A final prediction is that increasing specificity of any spatial relation to be produced or recognized increases the difficulty of managing that relation.

This model clearly requires further refinement. We cannot specify, for example, if these elements contribute incrementally or synergistically to the difficulty of a problem. Nor can we specify in what order a novice approaches the elements of spatial relations in the course of learning to solve a problem. Nevertheless, core predictions from the model are eminently testable, by systematically varying the number, specificity, dynamic status, and sequential or concurrent relational requirements embodied in a problem. For example, one may present two (or more) groups of subjects with food-retrieval tasks that range from producing a single non-specific, direct, static relation (such as retrieving honey from an open container by direct reach with the hand) through problems with multiple concurrent dynamic specific indirect relations. Requiring the use of a stick makes the necessary spatial relation indirect. Modifying the container can make the relation between stick and container more specific. Presenting bits of dry food on a tray requires the actor to use the stick to slide each piece of food across the tray, making the relation between stick and food dynamic (because the food can move with respect to the stick; the actor has to monitor the relation between stick and food as retrieval progresses). A second sequential relation can be added by introducing a second action to complete the task (e.g., pushing the food into a cup). A concurrent, dynamic relation can be added to the problem, for example, by introducing irregularities in the surface of the tray (holes or barriers), which must be avoided or surmounted. A similar series of problems could be presented, in which the subject predicts the location of an object moving across varying terrains. We have presented results from individual studies containing some of these elements that are congruent with the model (indeed, they resulted in its development), but testing the model requires prospective, systematic work.

We hope to have convinced the reader that studies of spatial reasoning offer valuable contributions to behavioral and cognitive neuroscience, particularly because we are now in a position to forge links across scientific disciplines that heretofore have been absent. We have examples of effective behavioral and neurophysiological methods to study spatial reasoning in nonhuman species, a body of behavioral data about spatial reasoning in several species of nonhuman primates, and a growing body of data from one species of nonhuman primate on the neurological correlates of learning to use an object as a tool. We have complementary data and conceptual frameworks concerning spatial problem solving in humans that enrich and inform the comparative findings. Here, we have presented a theoretical framework that we hope permits more explicit links between studies of spatial reasoning in humans, including developmental studies, and studies of spatial reasoning in other species. We have a particular interest in tool use as a special form of spatial reasoning. Tool use in nonhuman primates, although written about much, has until now been approached descriptively more than theoretically, and in particular, theoretical models linking tool use in nonhuman animals to neuroscience and to development have not been prominent (see Visalberghi & Fragaszy, in press). Our framework affords a first step to correcting these lacunae, to make the study of tool use in nonhuman species more relevant to understanding the evolutionary, developmental, and experiential origins of skilled tool use in humans.

NOTE

1. Reasoning here used *sensu* Bermudez (2003) to mean all the mental processes involved in choosing among alternative courses of action.

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