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Relational spatial reasoning and tool use in capuchin monkeys

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ABSTRACT

I review 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) in these monkeys. I present a general model of relational reasoning that takes into account five properties of spatial relations that can be present in spatial problems. Spatial problems are classed as a function of how many discrete spatial relations must be managed, and whether the relations are managed successively or concurrently. Each relation is also classed with respect to three orthogonal properties as (a) simple or precise (with respect to position, orientation, or location), (b) static or dynamic (with respect to time), and (c) direct (through body contact) or distal (through an object acting on another object or surface). This model permits systematic examination of how different combinations and properties of these categories impact the difficulty of a problem. Capuchin monkeys master problems with one, two, or three spatial relations, and if more than one relation, at least two relations may

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be managed concurrently. They can master static and dynamic relations through direct and distal contact with objects, and with sufficient practice they can produce rather precise spatial relations through both direct and distal action. The relational model of spatial reasoning can support principled comparisons of fundamental cognitive processes across species.

Key words: Spatial cognition, embodied cognition, combinatorial manipulation

RESUMO

Reviso a solução de problemas espaciais por macacos-prego com a finalidade de entender a natureza de seu raciocínio relacional (quando dois ou mais elementos de um problema ou situação são consideradas em conjunto para a identificação de uma estratégia de ação). Apresento um modelo geral de raciocínio relacional que leva em consideração cinco propriedades das relações espaciais que podem estar presentes em problemas espaciais. Os problemas espaciais são classificados em função de como várias relações espaciais discretas devem ser manejadas e se elas são manejadas sucessiva ou simultaneamente. Cada relação também é classificada em função de três propriedades ortogonais em (a) simples ou precisa (em referência à posição, orientação ou localização), (b) estática ou dinâmica (em referência ao tempo) e (c) direta (através de contato corporal) ou distal (através de um objeto agindo sobre outro objeto ou superfície). Este modelo permite a análise sistemática de como diferentes combinações e propriedades destas categorias influenciam a dificuldade de um problema. Os macacos-prego dominam problemas com uma, duas ou três relações espaciais e quando há mais de uma relação, pelo menos duas podem ser manejadas simultaneamente. Eles podem dominar relações estáticas e dinâmicas através de contato direto ou distal com os objetos e com prática suficiente podem produzir relações espaciais relativamente precisas através de ações diretas e distais. O modelo relacional de raciocínio espacial pode permitir comparações interespecíficas de processos cognitivos fundamentais.

Palavras-chave: Cognição espacial, cognição personificada, manipulação combinatória

INTRODUCTION

Reasoning about spatial relations (where two or more elements of a problem or situation are considered together to arrive at a course of action) 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 rely upon (a) movement of an object in one place that 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., spear); (b) skill at placing two or more objects in specific relation to each other to produce a new kind of material (e.g, braiding rope, weaving fiber), or (c) using one object to fix another in place (e.g. tying with rope, fastening with a peg).

Humans clearly can, especially with appropriate training and practice, 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, mastering spatial reasoning presents an enormous and continuing challenge - the technological insights mentioned above occurred over millennia. The relational complexity of various tools is one explanation given for the ordered appearance of stone tools of different varieties in the paleo-archeological 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 three millennia in Gujarat, India, require seven or more years of apprenticeship to become masters (Roux *et al.*, 1995).

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 I consider how capuchin monkeys (*Cebus* sp.) reason about spatial relations in the course of solving problems involving moving objects in two – and three-dimensional space. Capuchin monkey species are apt for this enterprise for several reasons, most notably that they spontaneously manipulate objects in ways that produce spatial relations between objects and surfaces, and that they spontaneously use objects as tools (see Fragaszy *et al.*, 2004a, 2004b, for a detailed review). Both of these characteristics are anomalous among monkeys but are shared with humans, and they indicate the potential for some degree of human-like spatial reasoning in capuchin monkeys. Thus capuchins offer one of our best opportunities to find elements of spatial cognition shared with humans, but without the complicating factor of language.

I present a conceptual model of spatial reasoning that builds upon ideas presented by Lockman (2000), Bushnell & Boudreau (1996), and others who have conceptualized object manipulation from the standpoint of actions that take place in space and time. These ideas derive from the seminal theory of J. J. Gibson (1966, 1979), known now as ecological psychology (see Gibson & Pick, 2000). My model also incorporates concepts from dynamic systems theory, as applied to behavior by Thelen & Smith (1994), for example. The model (hereafter, relational model) incorporates the nature and number of spatial relations, their temporal relation to each other, their specificity, and their duration and stability over time (Table 1). In the first part of this paper I describe common actions that capuchins perform with objects and that involve the production of spatial relations, and analyze these actions in the terms of the conceptual model of spatial relations. In the second part I apply the relational model to tool use, and in the third part, I illustrate the model's application to examples of tool use by capuchin monkeys. A more extensive application of the model to the behavior of capuchin monkeys is presented in Fragaszy & Cummins-Sebree (2005).

Part I: Actions combining objects with surfaces and with other objects

Capuchins frequently combine objects and surfaces, or objects with other objects. Such actions are commonly labeled "combinatorial actions" (Table 2). 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 (Fragaszy *et al.*, 2004b; Janson & Boinski, 1992). 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

Table 1. Properties of spatial relations produced, used, or embodied in action.

Property	Variants
Number of relations	Variable (1, 2, 3, etc.)
Specificity	Permissive vs. specific
Temporal order of production	Sequential vs. concurrent
Relation to body	Direct vs. indirect
Temporal nature of control	Static vs. dynamic

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

(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, Table 2 presents them classed by two orthogonal factors drawn from the relational model: the number of spatial relations (the order) embodied in the actions, and the degree of specificity of the orientation between the two objects or object and surface produced by the actor (represented in the table with two states, permissive and specific). In zero-order actions, the actor manipulates an object or surface directly. First-order actions combine an object with a fixed substrate or another stationary object. Permissive first-order combinations require only that the object and surface be brought together; specific alignments are not needed. The overwhelmingly most common combinatorial actions capuchins produce in captivity and in nature, rubbing and pounding an object against a substrate, are first-order combinations. In most cases, these are permissive 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.

Table 2. Relations embodied in common actions with objects and substrates performed by capuchin monkeys.

Relational category	Definition	Examples
Zero order		
Permissive	Act directly with the body on a surface or an object	Bite, hit, rub, scrape, pull, etc.
Specific	Act on a target zone of a surface	Bite at a certain location on a branch Insert a hand into an opening
First order		
Permissive	Combine an object with another object Combine an object with a surface	Bang one block on another block Bang a block on a perch or a fruit on a branch
Specific	Combine an object with a surface Combine an object with another object, where the moved object is oriented or aligned to the other	Rub or bang specific side of fruit against a surface Insert a stick into a hole Insert an object into a cup held in the hand
Second order		
Permissive	Combine one object with two others	Insert one cup into stack of two or more others, when cups are all the same size
Specific	Combine one object with two others	Insert one cup into its place in the middle of a seriated set of cups

First and second order actions are commonly identified as “combinatorial”.

Specific first-order relations require producing a particular spatial relation (such as alignment) between object and substrate. We have many examples of capuchin monkeys producing specific first-order relations between an object and a fixed substrate. Izawa & Mizuno (1977) provide a striking illustration of specific first-order combination in their descriptions of tufted capuchin monkeys opening hard fruits by pounding them against the protruding growth node of a bamboo trunk. Sometimes monkeys consistently pound the longer axis of an elliptical or linear object in a perpendicular relation to the tree limb or other relatively straight edge, in essence using the substrate as a fulcrum (Boinski *et al.*, 2001; Panger, 1998).

Combining loose objects with each other is also a first-order action. 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 bang two snails against each other occasionally (D.M. Fragaszy, unpublished data). A captive monkey in my laboratory provides a compelling example of a specific first-order action with two objects. This monkey habitually holds one piece of chow (which is quite hard, like very dry bread) 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.

A second-order combinatorial action involves combining one object with another, and concurrently or successively combining the paired set with a third object or substrate. We have one example of wild capuchin monkeys producing second-order combinations while manipulating objects. Capuchin monkeys in the State of Piauí, Brazil, routinely pound open nuts they have placed on stones by using a second stone (Fragaszy *et al.*, 2004a; Ottoni & Mannu, 2001, describe a similar phenomenon in semi-free 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 stone tools by a population of monkeys involves hammer and anvil use.

Part II: Producing and managing relations in tool use

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. A relational perspective brings us to include an additional element in the definition: an individual uses a tool only when the individual produces a relation between the tool and another object or surface. This addition excludes some actions that others 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 (e.g., Hauser, 1997). 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 *et al.*, 2004b). 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, prompted the development of the relational 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 (the "tree model"), shown in Figure 1 is 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 notes, a sequential behavior following an embedding rule can have

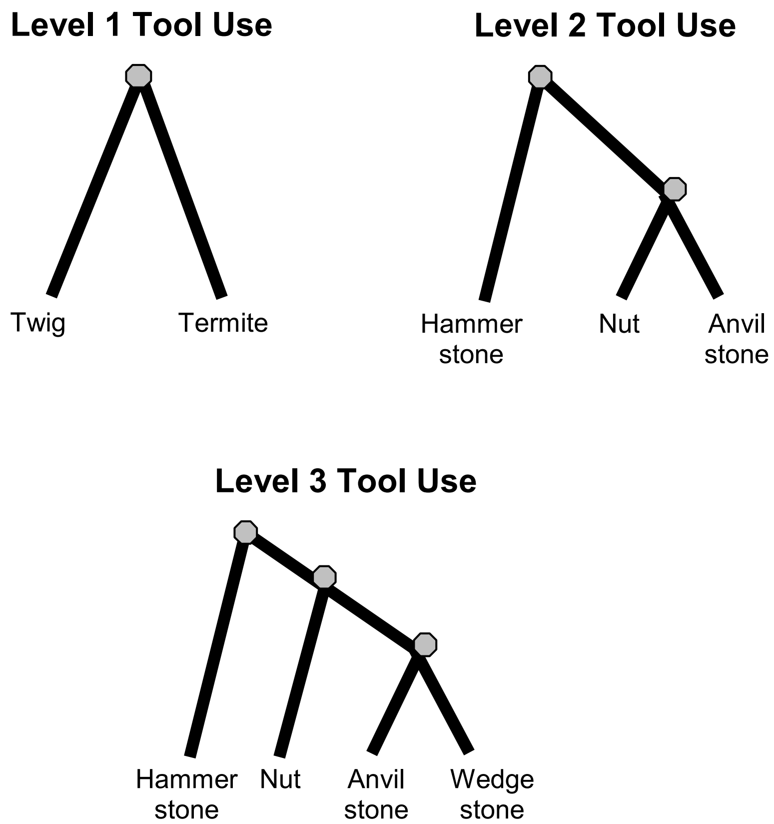

Figure 1. Matsuzawa's (2001) hierarchy of tool use using the tree-structure analysis. According to the relational model, the example of Level 1 Tool Use given in the tree structure model (using a twig to collect termites) is a static, direct action producing one spatial relation. The relational model 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 the specified in the 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.

an infinite number of nodes in the tree, and the complexity of the resulting tree structure is indicated by the depth (number) of nodes. Figure 1 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 and Matsuzawa 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 (Gibson, 1979; Gibson & Pick, 2001; Lockman, 2000), impact the problem in substantive way (see Table 1). Specifically, they 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).

Table 3 gives some examples of spatial relations evident in common actions with objects performed by capuchin monkeys. The properties in Table 3 include two that are familiar from our treatment of object manipulation (see Table 2) (number of relations; specificity of each relation). To recap, specificity of relations refers to the requirement for a particular alignment or orientation of one object to another or to a surface for effective use. Using a claw-head hammer to strike a nail is an example of a tool-using action that involves producing a specific relation, in this case, orienting the flat side of the claw-head hammer downward to strike the nail. In contrast, using a stick to probe into a container of honey, for example, does not involve producing a specific relationship between stick and honey – any part of the stick that is inserted far enough into the container will work, and the honey is an amorphous material, with no differentiated segments. Although specificity is treated as a unitary binary element in this table, 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 accommodation during action to specific spatial requirements (Berthoz, 2000).

Table 3 includes three additional properties of spatial relations not illustrated in Table 2. Two are straightforward, and apply only when more than one relation is produced. The first of these has to do with whether a particular relation is produced or managed concurrently with any other (concurrent or sequential). Managing two relations concurrently is more difficult than managing two relations in sequence, as noted in other contexts by Case (1992), in line with the attentional demands that must be devoted to each. The second property is whether the spatial relation is managed by a direct action linking the body and object, or an indirect action, where an object is intermediate between the body and the second object in the relation. In the latter situation, the actor must anticipate and monitor the distal, indirect consequences of its direct action, as in using a rod to move a hook on a line into position to snag something floating in the water. The actor is moving the rod; the rod is moving the line, and thus the hook at the end of the line. This task has more degrees of freedom, and therefore requires more attention to action, than a direct, single-relation action. Placing the rod directly onto the floating object is much easier than moving the line, and thus the hook, hook to snag the object. In principle, two concurrent relations could both be direct – as when holding a screw in one hand at the point of insertion in the wood surface, and holding a screwdriver in the other hand. This scenario embodies two relations (screw to wood, and screwdriver to screw), and each of them is controlled directly by the body.

The third property applies to all spatial relations, and pertains to the temporal quality of maintaining the spatial relation. A spatial relation can be static, in that it is produced once, as an event, and the

Table 3. Relations produced through action with an object evident in capuchins' use of tools.

Example of action	Number of relations	Temporal properties among the actions producing spatial relations	Static or dynamic	Direct or indirect
Pull in a cane positioned with food inside the hook and the straight part of the cane within reach Pull in cloth with food on the cloth	0 (NOT TOOL USE)	NA	Static	NA
Probe into an opening with a stick ("dip") Pound a stone on a nut fixed on a surface	1	NA	Static	Direct
Push food out of a tube with a stick Pull in an object with a stick when the stick must be repositioned to maintain contact with the food during pulling Pound a loose nut with a stone, where the stone may move when struck	1	NA	Dynamic	Indirect

Continues

Continuation Table 3

Example of action	Number of relations	Temporal properties among the actions producing spatial relations	Static or dynamic	Direct or indirect
Pound a stone (b) against a loose nut placed stably (and released) on a second stone (a)	2	Sequential	(b) Dynamic (a) Static	Direct
Push food through tube (b) with a stick while avoiding a hole (a)	2	Concurrent	(a) Dynamic (b) Dynamic	(b) Direct (a) Indirect
Pull food with a rake (a) while avoiding a hole in the surface (b)				(a) Direct (b) Indirect
Pound a stone against a nut on an anvil surface (a) while holding the nut (b)				(a) Direct (b) Direct

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relation remains in place. Putting a puzzle piece into a partially completed puzzle is an example of producing a static spatial relation; the piece is inserted once into a stationary substrate and released. That is the end of the action; the momentary event of placement has produced an enduring spatial relation. Alternatively, a spatial relation can be dynamic. Consider holding a cursor, controlled by a joystick, inside the circumference of a marked "target" that moves erratically across a computer monitor. The initial placement of the cursor in the right position must be followed by sustained effort to keep the cursor in the right place. This is a dynamic spatial relation; it demands ongoing monitoring and adjustment. This is not an event; it is a process. Keeping the head of the screwdriver in the slot of the screw head as it turns the screw is an example of a dynamic relation present when using a tool. Dynamic spatial relations demand more sustained attention from the actor than static relations because they must be managed over time.

Table 3 gives examples of possible combinations of single-relation actions and a subset of 2-relation actions in tool-using, illustrating some of the possible combinations of relations as specific or permissive, static or dynamic, sequential or concurrent relations, and if concurrent, direct or indirect. Below I examine the results of a few recent studies of tool use in capuchin monkeys with respect to these five properties. Tasks that make use of the same kinds of tools (sticks to probe, for example) can vary in the five properties that we have identified as important in analyzing the cognitive demands of tool use. This table makes it clear that analyzing the complexity of tool use can benefit from consideration of additional properties of the actions beyond the number of spatial relations that, eventually, appear in the complete sequence, as the tree model addresses.

Part III: Application of the relational model to examples of tool use by capuchin monkeys

A. Using shaped sticks (hoes, canes) to pull

Researchers have given nonhuman primates of several species a shaped stick (hoe, cane, rake; hereafter all referred to as "stick") to pull an object within reach (chimpanzees: Povinelli, 2000; Tomasello *et al.*, 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 *et al.*, 1996; baboons: Beck, 1973;

Tonkean macaques: Ueno & Fujita, 1998). Capuchins readily master using sticks to sweep in objects (adults: Cummins-Sebree & Fragaszy, 2005; Fujita *et al.*, 2003; infant: 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 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 not producing any spatial relation when it pulls in the stick, and therefore the action does not qualify as tool use. This would be equivalent, in relational terms, to withdrawing a pre-placed stick from a container of honey. However, when the actor must produce and/or monitor at least one 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 bring the blade just behind the food, so that they could pull it in, no matter where the food was on the tray. That this is not a trivial problem is illustrated by the difficulty encountered by Japanese macaques given a similar problem by Ishibashi *et al.* (2000). These monkeys 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.

Cummins-Sebree & Fragaszy (2005) assessed whether capuchins could produce specific spatial relations between sticks and food by presenting variously shaped sticks to capuchin monkeys together with a piece of food to retrieve (Figure 2). In this case, the monkeys frequently rotated and turned the objects to achieve a specific spatial relation between a part of the stick and the food. 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 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. 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 pre-existing relation. However, the capuchins also managed the first-order relational version of the cane problem, where they actively produced an appropriate spatial relation between tool and food by rotating and repositioning the tool. 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 20-46% of the trials in which they repositioned the tool.

The capuchins occasionally had to reposition the sticks presented by Cummins-Sebree & Fragaszy (2005) to produce effective contact between the tool and food; they also had to maintain that contact while moving the food. Thus, this task incorporated multiple elements of our spatial coding scheme. Repositioning the tool, then using it for retrieval involves producing sequential relations. This is also a dynamic task that required indirect contact with the food (through the use of the tool), and depending on the contours of the tool, could have been a specific or permissive task (specific if the surface area used to make contact with the food was at a minimum; permissive if the surface area was at a maximum).

I have presented details of just one study in which capuchins used sticks as tools, but others have been conducted, both in my lab and by other investigators (see Fragaszy *et al.*, 2004b, for a review). To

Figure 2. Capuchin monkey moving a shaped stick to produce a specific spatial relation between the stick and a piece of food. After it placed the stick behind the food, it pulled the food within reach and retrieved it (photo by Sarah Cummins-Sebree).

summarize the monkeys' use of stick tools in my laboratory, the tasks presented to capuchin monkeys have incorporated one or two 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 and effective spatial relation between tool and goal object). However, in all these problems, precise control of the distal end of a long tool was 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).

B. 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 one or more spatial relations, and these relations can vary in all the dimensions listed in Table 2. In the simplest circumstance, 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 a specific surface (hereafter, 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 first-order problems, those in more natural settings include second-order relations. I focus on studies concerning dynamic single and dual-relation problems.

C. 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 two years old using a hard object to crack open loose nuts (Anderson, 1990; Resende *et al.*, 2003).

Very recently, Fragaszy *et al.* (2004a) documented that a population of wild capuchins in Piauí, Brazil, uses stones to pound open nuts placed on an anvil surface. This is an important discovery, as the form of the activity is exactly that noted for wild chimpanzees in some parts of western Africa (Boesch & Boesch-Achermann, 2000; Inoue-Nakamura & Matsuzawa, 1997) (Figure 3). 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), which is quite specific, as the monkeys place the nut repeatedly in different places on the anvil, apparently until it rests without rolling. Then, the monkey strikes the nut with a heavy hammer stone (weighing on average 1.1 kg; Visalberghi *et al.*, 2007), producing a sequential, static, permissive, direct relation between hammer stone and nut. Capuchins living in semi-free conditions crack nuts in a similar manner using hammer stones and anvil surfaces (Ottoni & Mannu, 2001). The monkeys studied by Ottoni & Mannu cracked much smaller palm nuts than the wild monkeys observed by Fragaszy *et al.* (2004a), 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.

Cracking a nut with a hard object involves, at minimum, producing one static, direct, permissive 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 anvil 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.

Figure 3. A wild capuchin monkey (*Cebus libidinosus*) cracking a palm nut with a stone, using a log as an anvil. The nut is visible on the anvil, immediately below the stone (photo by Tiago Falótico). The recent discovery that populations of wild capuchin monkeys use stone tools and anvils opens up new opportunities for the study of relational actions in natural settings in this genus (see Fragaszy *et al.*, 2004a, for further information).

CONCLUSION

The action-perception perspective that informs this review, and my model of relational spatial reasoning, 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 considers knowledge as embodied in action and emphasizes that learning to do any skilled action (including using objects as tools) reflects discovery through actions, perceptual learning, and practice in a particular context (Bernstein, 1996; Gibson & Pick, 2000; Smitsman, 1997). For problems involving tool use, this perspective calls for an analysis of the 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 (Gibson, 1979; Gibson & Pick, 2001; Lockman, 2000).

From this point of view, to understand the basis and limits of capuchins' abilities to use objects as tools, we need to look at how quickly and how precisely capuchins master object relations and how many relational elements they can manage at one time. We also need to look at the physical aspects of moving objects and applying force with them; for example, how the monkeys improve their control of placement, force, tempo, etc. These are not trivial aspects of learning to use an object as a tool, as anyone who has worked to master a new skill can verify. We can also look at the contributions of different forms of perceptual information (kinesthetic, visual, auditory, etc.) to precise placement and alignment of objects and their movements across surfaces. Experimental work on these issues with capuchins is just beginning, so we can as yet draw few conclusions. One prediction that this perspective brings is that capuchin monkeys will master tasks most readily in which the relations between action and outcome are immediately perceptible to them, and as a corollary, that proprioceptive and auditory (as well as visual) information about the outcomes of actions with objects will be helpful for them.

Here, I have presented a theoretical framework that I hope permits more explicit links between studies of spatial reasoning in humans, including developmental studies, and studies of spatial reasoning in other species. I 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 behavioral development have not been prominent (see Visalberghi & Fragaszy, 2006). The relational model affords a first step to correcting these lacunae. I hope that it can 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.

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