Anim Cogn (2006) 9:235–245
DOI 10.1007/s10071-006-0043-6

REVIEW

Animal logics: Decisions in the absence of human language

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Received: 26 May 2006 / Accepted: 22 July 2006 / Published online: 15 August 2006

Human beings are rational animals, in other words, they have logic. The word 'logic' has a double meaning, as it describes both a way of thinking and one of the most ancient intellectual disciplines, with its beginnings going back to the 4th century B.C. According to the second meaning, logic is the science of reasoning. Not only because of its long history, but also mainly because of its strong influence on society, it can be viewed as the backbone of Western civilization, holding together its systems of philosophy, science, and law. Obviously, the authors of this special issue on 'animal logic' refer to the first meaning, by describing the findings of state-of-the-art research on how the mind of human as well as nonhuman animals works. However, this strain of science cannot be decoupled from the historical approaches to the study of the mind, as they have been unfolded in philosophy, psychology, and logic. As the papers in this issue demonstrate, many phenomena studied now in animals have been studied in humans, or have distinct philosophical roots of conceptualization. Inferential and causal reasoning, mind reading, and the formation of concepts, to mention the most popular, are concepts of cognitive processes framed traditionally in logic and the philosophy of mind. Building on traditional terminology and concepts does not necessarily mean to fall into the trap of the 'animal model anthropocentric view', an approach that is oriented towards using animals as model systems for understanding humans. Even if we want to understand animals and their ways of thinking in their own right, it would be unwise to neglect or dismiss the historical approaches of the study of mind. Recent collections of papers exemplify the value of exploiting and applying the frameworks of logic, rationality, and philosophy of mind to describe and compare phenomena in animal cognition (e.g., Heyes and Huber 2000; Bekoff et al. 2002; Hurley and Nudds 2006). An international symposium at the Konrad Lorenz Institute for Evolution and Cognition Research in late 2004, supported by the 21st Century Centre of Excellence at Keio University, Tokyo, was explicitly devoted to the question of what evidence is available to describe some aspects of animal cognition as "logical". This special issue arose from that symposium, but also includes contributions from invited authors who seemed to us excellent choices for necessary supplements, in order to pursue this question both theoretically and empirically.

This contribution is part of the Special Issue "Animal Logics".

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Historical roots of the logic of mind

The history of logics tells us that the discipline started as an inquiry into truth-preserving arguments. Aristotle's (384–322 B.C.) first and main concern was to create a tool (organon) to argue convincingly. By discussing sentences he discovered the syllogism, that is, if an argument of three statements is built where the subject of the first statement is the predicate of the second (called the premises) and the third statement is composed of the remaining terms (called the conclusion), the truth of the conclusion is guaranteed by the truth of the premises. For the German philosopher Gottfried Leibniz (1646–1716) logic was no longer only a tool for convincing arguments, but rather a universal system of rules of thought, so that even God's thought is necessarily logical. The modern science of logic began with Gottlob Frege, who introduced a propositional calculus, developed in conjunction with the problem of founding mathematics and solving problems in language. Of course, this conception of so-called formal logic is hardly useful for the description of cognitive processes in non-linguistic creatures. But common-sense understanding guided people's conception of animals in the past of sharing with us the capacities of logical thinking and reasoning. The use of animal courts in the medieval Western culture is an example of such a view. Animals were considered to act for a reason, hence are responsible for their behavior. If they violated laws, they had to be judged and punished like humans.

The scientific use of logic underwent a major paradigm shift in the 20th century when proponents of the classical view had trouble in describing the way the world is. A good example is the Sorites paradox of asking how much is a "heap". Many contemporary philosophers and logicians have become rather upset by the narrow conception of classical logic and agreed with Carnap on the tolerance principle, according to which there is not one but many logics. One consequence of this was the creation of non-classical logics, collectively called "fuzzy logic," providing better tools of describing, for instance, processes of pattern or object recognition.

However logic has been defined, many philosophers and psychologists have agreed on the assumption that the brain is a machine that follows logical rules. Cognitive science in the mid-20th century was largely inspired by computational models of reasoning, proposing formal symbol processing as a metaphor for all cognitive activity. However, studies in economics and of human decision-making document cases in which everyday and expert decision-makers do not live up to the rational ideal. Systematic analysis has revealed interesting and persistent patterns of our departures from ideal logician (Tversky and Kahneman 1974), and from Freud to modern cognitive science there is agreement that the rationality of men and women is frail and suspect, and that various quite unconscious motivations and methods of inference underlie some of our simplest subjective impressions of reason. While logical omniscience might appropriately characterize a deity, it is at odds with the most basic law of human psychology. Rationality is 'bounded' because it is exhibited by decision-makers of limited abilities, and it is far from being a tool for optimizing or maximizing, but only serves the agent "satisfying" its expected utility, choosing decisions that are good enough according to its belief-desire set, rather than perfect (Simon 1982). Such moderate rationality conceptions leave room for widely observed phenomena of suboptimal human reasoning, rather than excluding them as unintelligible behavior. These more psychologically realistic models of human decision-making can explain the departures from correctness as symptoms of our having to use more efficient but formally imperfect "fast and frugal" heuristic procedures (Hutchinson and Gigerenzer 2005).

Full-fledged rational thinking might be a human faculty, but it might be restricted to rare situations (e.g., scientific thinking). Everyday reasoning might be better described as "ratiomorphic," a term invented by Brunswik (1955) to characterize processes that are "closely analogous to rational behavior in both formal and functional respects, [but] have nothing to do with conscious reason." Lorenz (1977) and Riedl (1984) distinguished a system of 'innate forms of ideation,' which allows our anticipation of space, time, comparability, causality, finality and also a form of subjective probability to jointly form a system of unconscious, sub-personal human thinking. For instance, when people are confronted with a series of events and are asked to decide whether it is rule-based or stochastic, two different problem-solving strategies may be applied (Riedl et al. 1991). In contrast to a rational one, which is based on conscious calculation of probabilities, the 'ratiomorphic' strategy is based on an iterative comparison of weighted confirmations and disappointments.

Attention has therefore turned to evaluation of uncritical idealizing. Probably much of the ground plan of our species' model of an agent is innate; the framework therefore may be a ladder we cannot kick away. On the basis of Darwinian evolution, it seems reasonable to assume that specifically human abilities are not entirely unrelated to those of our animal relatives, and of course there are many aspects of human behavior that are by no means specifically human. However, while this general statement may be easily accepted one and a half century after Darwin, when it comes to 'higher' cognitive processes like reasoning and abstract thought, comparative research is still in its infancy. Nevertheless, as the collection of articles in this special issue will show, we have made some important steps away from the utterly pessimistic notion of Bower and Hilgard (1981) that the origin of inborn organization of human reason in detail is still a complete mystery.

As a starting point, we agree with Hurley (2006) that one should be careful not to over-intellectualize what it is to have a mind, or in viewing rationality as all or nothing. By allowing that rationality can be disaggregated into domain-specific capacities within which basic features of practical rationality are nevertheless present, we can characterize the animal level in terms that are neither too rich nor too impoverished, and chart various specific continuities and discontinuities between our minds and those of other animals.

Logic and language

Since Aristotle, it is a widely held view that logic and language are tightly connected in the human mind. Both involve intentionality and an interaction of syntax, semantics, and pragmatics. Logicians like Hilbert and Frege developed formal systems, mathematical models of reasoning based on the syntactic manipulation of sentence-like representations. Within linguistics, this has led to the view that a sentence has an underlying logical form that represents it's meaning, and that reasoning involves computations over logical forms. Also for Wittgenstein, logic was something that both the world and language have in common. Therefore language can be used to picture the world, so it is only because of logic that our sentences have any meaning at all.

However, in contrast to adherents of logical positivism, many had doubts that logic is so vital. Even Wittgenstein in his later period moved away from the faith in logic he held as a young man. He reflected on the value of commonsense language concepts, a view that was thereafter shared by psychologists and linguists. Empirical evidence challenged the classical or "Lockean" position of categorization as a conceptual or inferential process working on the arbitrary perceptual categories of the world. Thus, the distance between logic and language increased steadily, which was also reflected by a refocus of logicians like Gödel – whose 100th birthday we honor – on normative questions of reasoning, of what makes a principle of reasoning valid or invalid.

Concerning the relationship between logic and language, we are witnessing today a contrast between views on the underlying structure of human reasoning. Some argue that humans possess a mental or natural logic, which is defined as a set of simple inference rules that are required to understand language and to reason about everyday practical matters (e.g., Braine and O'Brien 1998). For them, the rules of mental logic are universal, present in all languages, and fully mastered by adults. According to Piaget (1970), this human cognition qualifies as formal, 'hypotheticodeductive,' developing adolescence at about the age of 14 or 15. On the other hand, Johnson-Laird (2001) has proposed the opposing view that we can reason without logico-linguistic rules, but instead cognition takes place in a visio-spatial workspace. At the moment, both views – mental logic or mental model – are supported by behavioral data.

Fortunately, we can now test the opposing theories using brain-imaging techniques, investigating which brain areas are recruited for solving deductive tasks. As a first important result, current evidence suggests a compromise between both theories, because different brain networks – logico-linguistic or visio-spatial – are activated depending on whether the reasoning problem to be solved has semantic content (Goel et al. 2000). Deductive logic recruits mainly linguistic brain areas in a left fronto-temporal network (Wharton and Grafman 1998), whereas arithmetic computation relies principally on visio-spatial brain areas in a bilateral parieto-frontal network (Dehaene 2002). But will neuroscientists also discover a brain device shared by logic and mathematics using not only arithmetic tasks but also complex mathematical reasoning tasks that require deductive-logic skills (Houdé and Tzourio-Mazoyer 2003)? It is still a challenge for the future to clarify how language, logic, and mathematics interact in the human brain.

This question fits well with insights into the functional relationships between language and cognition in humans and animals, especially for numerical cognition. Hauser et al. (2002) suggested to delineate two more restricted conceptions of the faculty of language, one broader and more inclusive, the other more restricted and narrow. The faculty of language in the broad sense includes a sensory-motor system, a conceptual-intentional system, and an internal computational system. This latter abstract linguistic computational system has been suggested to be the only uniquely human component of the faculty of language, providing the capacity to generate an infinite range of expressions from a finite set of elements (recursion).

The main hypothesis entertained by Hauser and colleagues (2002) is that recursion may have evolved for reasons other than language, but became domain-general in humans, operating over a broad range of elements like numbers and words. In animals, by contrast, recursion has evolved as a modular system serving a particular computational function in the non-communicative domain, but is impenetrable with respect to other systems. The problems considered to be solved by non-human animals with recursive-like computational abilities are navigation, number quantification, and social relationships.

But are animals really confined to display recursive-like abilities only in the non-communicative context? Only very recently, European starlings demonstrated the capacity to recognize complex recursive structure in songs (Gentner et al. 2006). These tiny birds distinguished between two different types of sounds; one allowed for a sound to be inserted in the middle of a song, a simple form of recursive center embedding similar to human grammar, the other followed the finite state rule, whereby a sound could only be added at the beginning or end, a type of structure attributed to non-human communications. While this report might, on the one hand, challenge the traditional 'Chomskian' position that what makes human language unique is a singular ability to comprehend these kinds of recursive patterns, it on the other hand fits nicely into the argument that the abstract computational (logical) capacity of language consists not so much of a single innovation as a novel evolutionary reconfiguration of many ancestral cognitive components, integrated into a new whole (Hauser et al. 2002).

Comparative psychologists and ethologists are therefore invited to look for evidence of such computations not only in the domain of communication, as has been extensively done in the many 'language projects' with great apes, sea mammals and parrots (see review in Hillix and Rumbaugh 2004), but also in problems involving number comprehension, navigation, and social relations in a broader range of species. With this approach, we are more likely to pinpoint the mechanisms underlying language and the selective pressures that led to it.

Logic without language

Of course, language forms an essential part of human reasoning, but in contrast to the strong 'Whorfian' proposal ("linguistic determinism"), we can think before and without language. The strong Whorfian hypothesis rules out the possibility of thought in animals and humans who lack language, although there is abundant evidence for the capacity of quantitative inference about space, time, and number in (a) preverbal humans, (b) in individuals with language impairments, and (c) in non-human animals. An interesting example for reasoning without language in adults is temporal epilepsy. In some cases, patients cannot speak during mild epileptic seizure, but behave normally, thereby suggesting reasoning without language. Preverbal infants demonstrate some kind of reasoning or have a naive theory of the world. For example, 4-month-old children predict movement of objects by gravity (Spelke 1990; Needham and Baillargeon 1993). An example from non-linguistic animals is provided by rats that represent the geometric structure of the environment (Gallistel 1990).

Numerical abilities in animals may be regarded as most appropriate possibility to study some forms of logic without language. Although many philosophers claim that logic requires language, because it offers the unique possibility of thinking about thoughts, the authors in this special issue of Animal Cognition agree on a wider conception of logic. For them, logic might have its apex in meta-representation, but is not necessarily restricted to it. Even for those who argue that logic in terms of formal operation on whole propositions or thoughts needs language, analogues of familiar reasoning processes are possible in the absence of linguistic structure (Bermudez 2006). Koehler (1950) described such behavior as "unbenanntes Denken" (unnamed thinking).

Research over the last decades has provided evidence for representations of number in a variety of non-human animals (for reviews see Davis and Pérusse 1988; Dehaene 1997; Gallistel 1990). Although a number of distinctive cognitive developments in children distinguish them from the most highly trained non-human animals, humans may have the same initial number capacities as other animals (Spelke and Tsivkin 2001; Gelman and Gallistel 2004). Research with animals and preverbal infants provides evidence for language-independent representations of numerosity with limited, scale-invariant precision and of exact numerosities for sets with four or fewer members (Gallistel 1990; Hauser 2000). This system supports simple arithmetic computation and plays an important role in elementary human numerical reasoning, whether verbalized or not (Butterworth 1998).

Support for the view that numerical capabilities are made possible by conceptual foundations rooted in our primate brain and thus reflecting a long evolutionary history comes from neuroscience. Nieder et al. (2002) report the discovery of number-encoding neurons in the lateral prefrontal cortex of the macaque brain. Together, these findings challenge the strong Whorfian view that a concept of number is dependent on natural language for its development (Gelman and Gallistel 2004). As stated so nicely by Dehaene (2002, p. 1653), "we are clearly not the only species with a knack for numbers". However, while small, exact numbers and large, approximate numbers can be represented independently of language, relying on nonverbal visio-spatial cerebral networks, representations of exact large numerosities depend on a specific language with a counting system (Dehaene et al. 1999). This latter arithmetic relies on language-specific representations and on a left inferior frontal circuit, which is also used for generating associations between words. Such symbolic arithmetic may be a human cultural invention evolved with the progressive improvement of number notation systems.

Evolutionary origin of logic

Although logical reasoning of humans may be based on some unique cognitive modules and distinct educational environments, basic mechanisms are undoubtedly the product of evolution. Darwin's enterprise was to show that our differences from other species were not major qualitative leaps, but were based on quantitative change that was due to basic evolutionary processes. Darwin thus tried to document that human behavior contained aspects that could be traced to our animal ancestors while at the same time arguing that the conceptual, communicative, intellectual, emotional, social, and moral aspects of our behavior also had roots in the behavior and psychology of other species. According to this view, logical thinking is result of natural selection or phylogenetic contingency.

Generally, if we focus on outcome, behavior is driven by mechanisms that evolved because they produce biologically useful behavior. Success is measured in the currency of inclusive fitness, i.e., the increase of the proportion of individuals carrying the respective alleles in the population (called "B-rationality" by Kacelnik 2006). The challenge for contemporary animal cognition research is to show in which way higher cognitive processes have been useful for survival and/or reproduction by figuring out the contexts in which a specific knowledge or understanding is important and the ways in which such knowledge confers selective advantage.

However, development of logical reasoning is not only straightforward adaptation. Many animals enjoy adaptation without advanced forms of cognition, by simply using "rules of thumb" to cope efficiently with the problems they face in real life. While most cognitive scientists think it is obvious that it is better to be smart than stupid, it is not obvious to the evolutionary biologist. Cognition does not come for free. The investment it presents has to be matched by the returns it provides. In other words, the benefits must be substantial.

Generally, cognitive behavior is more flexible than genetically preprogrammed behavior. The ability to act on information flexibly is one of the cornerstones of intelligent behavior. If the environment is constant, then animals do not need to change their behavior. Animals have to change their behavior only if the environment changes. Cognitive flexibility becomes valuable when variability affects the species in the long run. For example, seasonal changes in the environment may necessitate a change in foraging behavior. Difficulty in obtaining food requires deployment of flexible foraging strategies, sometimes even some sort of creativity and innovation (Reader and Laland 2003). For example, the kea, a New Zealand parrot, is a famous bird example. These birds are well known for their curiosity and they show skillful manipulation of objects (Huber et al. 2001). Like ravens (Bugnyar and Heinrich 2006), they show extremely quick solutions in tasks that have been used for testing 'insight' (Köhler 1921). The paper by Huber and Gajdon (2006) explores the underlying cognitive mechanisms.

One of the most popular theories of cognitive evolution, the so-called "social or Machiavellian intelligence hypothesis" (Byrne and Whiten 1988), challenged the view that primates need their intelligence to cope with the demands of a complex diet. It rests on the core assumption that the evolution of cognitive skills together with a large neocortex in primates was caused by the social complexity typically found in primate groups. Species in complicated societies must not only identify other members of the group, but also manipulate them by understanding their intention and the social relationships among them. What develops is a kind of cognitive "arms race" in which every adaptation by one individual is responded to by conspecifics with their own adaptation, which requires a counter-response, and so on in the "blood and claw" of survival of the fittest (Tomasello 2000). Some scientists suggested the origin of a typical form of logical reasoning, transitive inference, in the social setting. An individual's place in the social order can be learned through direct interactions with others, but conflicts can be time-consuming and even injurious. Because the number of possible pair-wise interactions increases rapidly with group size, members of large social groups will benefit if they can make judgments about relationships on the basis of indirect evidence (observation of interactions among others). For instance, social dominance hierarchies in troops of baboons consist of 80 or more individuals, of which each confronts 3,160 different dyadic combinations and 82,160 different triadic combinations (Seyfarth and Cheney 2002).

In asking whether monkeys are "logical," McGonigle and Chalmers (1977) tested them on transitive inference ability, producing appropriate responses to novel pairings of non-adjacent members of an ordered series without previous experience of this pairings. The ability to derive a relation between items that have never been presented together before has been used originally by Piaget (1937), creating a non-linguistic paradigm to assess the development of logical inference in children. Following Bryant and Trabasso (1971), the method involves replacing the premise pairs (or propositions) with simple simultaneous discriminations. McGonigle and Chalmers (1977) presented five overlapping pairs of stimuli: $A+\ B-$, $B+\ C-$, $C+\ D-$, and $D+\ E-$ (where the letters stand for different stimuli and the plus and minus signs indicate choices of the corresponding stimuli that are either reinforced or non-reinforced, respectively). In the crucial (transitive) test, subjects are presented with the novel pair BD. Successful ("logical") choice of B in the crucial (transitive) test of the novel pair BD is interpreted as indicative of transitive inference. The authors interpreted the consistent preference for B over D in their monkeys, together with various effects of series position on performance in a later study (McGonigle and Chalmers 1992) as evidence that some sort of explicit serration ability was within the monkeys' scope. Similar effects have been observed in chimpanzees, rats, and pigeons (review in Zentall 2001), tempting some researchers to conclude that (these) animals reason (Allen 2006).

With regard to pigeons, research, some researchers succeeded in demonstrating transitivity in pigeons (Kuno et al. 1994), others not (D'Amato et al. 1985). In many studies with animals, the stimuli were not transitive (like "taller than") but arbitrary (e.g., different colors) and the researchers assumed that their subjects could establish a transitive relation solely on the basis of reinforcement or non-reinforcement of the stimuli. The most common assumption was in purely associative terms, namely choice of B in the BD test being the result of the difference in their relative reinforcement history, with the ordered series of values $A>B>C>D>E$ as the outcome of the training procedure. This 'behavioristic' interpretation, reflected in a number of associative models (Zentall 2001), was indirectly supported by artificial neural network models showing transitive inference through backward error propagation. However, cognitive ethologists were reluctant to extend the results of associative learning experiments to explain the capacities of animals living in complex natural societies (Allen 2006). They reject the default assumption that behaviorism is the null hypothesis against which cognitive accounts are tested, and instead argue that transitive inference is an evolutionary adaptation to living in large, stable social groups. How should social coordination and the formation of alliances in such groups be simulated with the five-element paradigm consisting of only ten possible stimulus pairs?

Recently, Paz-Y-Miño and colleagues (2004) tested pinyon jays, a highly social member of the crow family with large, permanent flocks and clear pecking orders. The jays were allowed to observe individuals from other groups interacting over a peanut, and later interacted with some of those same birds. Actually, the pinyon jays infer social status transitively, having identified the individuals they watched and their roles in the observed encounter, and then retained this information for later use. Jays that had previously interacted with one of the birds they observed drew inferences about their rank relative to the demonstrator, and showed a graded, quantitative response based on their observations. Jays that observed very similar interactions, but had never interacted directly with any of the birds they observed, failed to show either effect.

It is tempting to assume that transitive inference is used in social life, and therefore species with more complex societies should be better at it. Indeed, a comparison of pinyon jays with the closely related, but less social, western scrub jay, provided some empirical evidence for this assumption (Bond et al. 2003). It is therefore not surprising that researchers working with pigeons are relatively inclined to suggest simpler explanations for behavior in transitive inference tests, being aware of the dangers of hypothesizing about unobservable cognitive mechanisms. However, only very recently, Lazareva and Wasserman (2006) tested pigeons with stimulus pairs that could be brought into a linear order (circles with decreasing diameter) or not. The pigeons preferred B to D in both situations, suggesting that the order of the stimuli did not affect pigeons' transitive responding (in contrast to rats with hippocampal lesions and hooded crows). Post hoc simulations showed that all currently available associative models failed to predict pigeons' responding in the BD test, thereby providing some support for the alternative spatial representation hypothesis. It proposes that an organism (in the original version by Gillan 1981, chimpanzees) integrates the independently presented premises into an ordered series of internal representations and that these representations are spatial in nature.

Support for the social origin of logical behavior also comes from studies with adult humans. Formal logic should be abstract and context-free, just like a mathematical operation, but we often deviate from this ideal logic. A well-studied example is the "4-cards-task," in which each card has a character on one side and a number on the other side. People are asked to detect a rule like "if D then 3" by turning over only two cards. Most human participants failed to get a correct answer in this context. However, in the version of a cheater task, humans easily got the correct answer (Cheng and Holyoak 1985).

A further interesting example for the possibility of emergent stimulus relations in animals is functional stimulus equivalence (Sidman 1990). If we learn $A = B$, then we infer $B = A$ (symmetry), and if we learn $A = B$ and $B = C$, then we infer $A = C$ (transitivity) and $C = A$ (equivalence). Do animals think similarly? Several researchers have investigated this problem (see review in Zentall 2001). Being trained in arbitrary matching to sample or symbolic matching to sample problems, a pigeon can learn a sequence, for example, if a triangle appears on the center key, to select a green key, and not a red key. The bird learns "triangle = green". In the next step, the green stimulus appears on the center key and characters "X" and "Y" appear on the side keys. The bird has to select the "X" when the green stimulus is presented on the center key. Now the bird learns that "green = X". Through this relational learning, humans infer new relations that have never been trained explicitly. One such relationship is symmetry, namely if the triangle is green, then green is triangle. The second is transitivity, namely if triangle is green and green is X, then triangle is X. The third one is called equivalence, that is understanding of "X is triangle" through relation of "triangle = green" and "green = X".

Most of the animal research failed to demonstrate emergence of equivalence (monkeys: Sidman et al. 1982, chimpanzees; Dugdale and Lowe 1990). One clear exception is the case of a sea lion (Schusterman and Kastak 1993). Animals living in social groups require higher cognitive demands. Schusterman and Kastak (1998) pointed out the social origin of emergence of stimulus equivalence in sea lions. They have a strong connection of mother-infant relation. Visual image, smell, and auditory signals of the mother are used to identify the mother.

Constraints by the nervous system

If logic is one result of a (specific) brain, it is somehow constrained by this organ. Because the brains are made of neurons, the logic has constraints by neurons. In other words, it has cellular-level constraints. And because different animals have different brains, there may be different limits in logical ability. In other words, it has system-level constraints.

Operation of advanced cognition involving a great deal of individual learning and of finding solutions to new problems, may need a complex organic system (a large brain relative to the body). However, this might be very costly for its owner in metabolic or energetic terms. Brains consume a large amount of glucose and oxygen. Reflection about reasons for its behavior, complex calculations, or finding logical consistency may take a longer time than pre-wired responses or simple decision processes based on 'emotional responses' or rules of thumb. Creatures equipped with cheaper and simpler decision mechanisms and control systems could be more adaptive than species with complex but expensive (in metabolic terms) systems. Analysis of the relationship between body size and brain size suggests that there are taxa that evolved larger brains (mammals and birds) compared to taxa with rather small brains. The lesson from evolution is that small-brain animals are equally adaptive as large-brain species as measured in terms of distribution across the animal kingdom. But interestingly, within each taxon there are large brain species, like apes (Reader and Laland 2002) and dolphins (Marino 2002) within mammals, corvids and parrots within birds (Iwaniuk et al. 2005), and some perciform species (Kotrschal et al. 1998; Bshary et al. 2002). Complex cognitive abilities evolved multiple times in distantly related species with vastly different brain structures in order to solve similar socioecological problems (Emery and Clayton 2004). The contributions to this special issue reflect this evolutionary fact of convergence in cognitive behavior despite divergence in the neuronal substrate.

Animal cognition studies have demonstrated that logical behavior is not human brain specific, but we can point out differences between human logic and animal logic also. One feature of human telencephalon is a well-developed cortico-cortical fiber connection. Such a connection is poorly developed in nonhuman animals. Thus, one area can be relatively independent from other areas in animal brains. Yamazaki (2001) trained pigeons on A = B, B = C and C = A relations, thus trained equivalence explicitly, and then tested symmetry and transitivity. The pigeons could learn the task, but showed neither symmetry nor transitivity. The results are "logically" impossible for humans. The neural basis of the independent existence of relationships A = B, B = C and C = A in pigeons may be a poor connectivity within the brain. Interestingly, Giurfa et al. (2001) clearly demonstrated the concept of sameness in honeybees. The insects showed transfer of MTS from the color dimension to the olfactory dimension. Although the bees and ants may be "ape in insects," their brains are completely different from vertebrate brains. We need further research to clarify system-level neural constraints of logical behavior.

Different logics

Piaget (1970) emphasized that psychological experimentation is indispensable in clarifying certain epistemological problems, among them why formalization can never be sufficient by itself. In addition to Gödel's theorem, which we mentioned above, the main reason is that there are many different logics, not just a single logic. No single logic, he argued, is strong enough to support the total construction of human knowledge. Furthermore, logical thinking is not a purely formal entertainment. One needs both developmental and evolutionary psychology in its broadest sense (see Heyes and Huber 2000) to explore the development of logical thinking. We suggest that the basic requirement for logical reasoning is a process called "abstraction," which is the identification of regularities in the environment and the formation of inner models or representations. Piaget (1970) distinguished between simple abstractions, abstractions from the objects in the environment themselves through experience, thereby generating physical knowledge. Logical and mathematical knowledge is also based on abstractions, but this time based on coordinated actions. Although language also serves to coordinate (communicative) actions, the roots of logical thought are not to be found in language. For both types of abstractions it is important to note that the distinctions are always gradual and not sharply discontinuous. There are graded shifts from concrete to abstract knowledge, as well as from individual to coordinated actions. Whereas the first is evident from studies of animal categorization, stimulus equivalence and object learning, the second is evident from tool use, planning and insightful behavior.

Complex cognitive skills that are typical for human adults, such as reading and calculation, and complex human achievements, such as formal science and mathematics, have been suggested to depend on a set of building-block systems that emerge early in human ontogeny and phylogeny (Spelke 2000). In contrast to the logic ideal, these 'core knowledge' systems are limited in domain and task generality by serving to represent a particular class of entities for a particular set of purposes. But we are able to combine representations from these systems to achieve extraordinary flexibility. The challenge now for developmental and evolutionary psychologists is to contribute to understanding unique features of human knowledge. For this endeavor, they can benefit a lot from comparison with non-human animals. Some have very similar perceptual and action systems and very similar systems for getting around in space, orienting in time, recognizing objects, and negotiating social encounters. Some are strikingly different, some are similar but have strikingly different brains. Studies of human and non-human animals of different age are mutually enlightening. If one result is that humans' cognitive achievements far outpace those of any other animal in formal domains, we may ask why this is so. It may stem in part from an enormous ability to combine old concepts and procedures to form new ones, with natural language being our most striking combinatorial system and formal mathematics being one of its richest and most dramatic outcomes (Spelke 2000). Alternatively, or in addition, the unique human cognition may stem from its collective nature acquired through a process called 'cultural learning' (Tomasello 1999). In cultural learning, young children learn to use the tools, artifacts, symbols, and other cognitive amplifiers of their culture by attempting to reproduce adults' intentional relations to them, or more precisely, adults' intentional relations to the world as mediated through these artifacts. But whatever the developmental causes for human cognition are, our interest in the core knowledge systems is reflected by the exploration of a diversity of animal logics by the authors of the papers that follow. Together they attempted to provide the readers of *Animal Cognition* with some basic facts and theoretical perspectives on nonhuman cognition in four different domains and many taxonomic entities.

The first type of logic may be called 'perceptual logic'. It is concerned with simple abstractions (according to Piaget 1970). For example, animals are sometimes required to reconstruct the three-dimensional world from the two-dimensional retinal image, they need to identify an object partially occluded by an obstacle, recognize the presence of an object that is temporally hidden by an obstacle. Lea and colleagues (2006) provide a theoretical consideration of the stimulus by providing evidence that different taxa are able to free themselves to various degrees from the stimulus logic by deploying an increasingly abstract logic. Watanabe and Troje (2006) offer a very sophisticated example of the stimulus logic. They produced computer-generated animations of pigeons to analyze conspecific recognition in these birds. Della Chiesa et al. (2006) investigate an important aspect of spatial cognition in animals, namely the ability of chicks to deal with the geometric properties of their surroundings. Benard and colleagues (2006) demonstrate very advanced forms of visual cognition in bees. Insects have traditionally been considered as 'Descartian' creatures, being nothing more than simple and small reflex automata. Giurfa's group now challenges this view showing that the behavior of honeybees displays an extremely rich behavioral repertoire that can be flexibly adapted to cope with a changing environment. In this issue, Benard et al. (2006) describe experiments showing (for the first time) that bees are able to categorize beyond pure generalization, that is, making classification on the basis of the extraction of class-defining features from objects of the animal's environment. The level of abstraction these animals may achieve is discussed.

The second type of logic is concerned with a specific understanding of the physical environment that we shall call 'technical logic'. Tools are a general comment on intelligence. The use and modification of tools requires several cognitive mechanisms. Tool users must understand means-end relations, object affordances and have specific motor skills. Obviously, the more an individual understands the functioning of a tool and the causal relationships by which the tool operates, the more effectively it can use it or change it to improve its effectiveness.

Both "tool using" and "tool making" need technical logic. A classical example of tool using is problem solving of a chimpanzee reported by Köhler (1925). A chimpanzee placed two sticks together and used them to get a piece of fruit overhead. Tool using has been observed to occur over a wide range of species. Pigeons also used a tool in a situation that was similar to that of Köhler's chimpanzee. The situation as described below is not real tool making, but the creation of a new combination of different behaviors. Pigeons, which had a history of training to move a box toward a particular position and to climb onto a fixed box and peck a suspended plastic banana, showed problem-solving behavior similar to that of the chimpanzee (Epstein et al. 1984). Pigeons that had no history of training to move a box to a particular position could not solve the problem. Thus, pigeons could interconnect different repertoires of behavior forming a new sequence to solve the problem, if they had a repertoire of each element.

Tool making requires more advanced cognitive ability and motor skills. Recently, Hunt and colleagues observed sophisticated tool manufacture of New Caledonian crows in the wild. In this issue, Hunt et al. (2006) explore the cognitive strategy underlying the selection of appropriate tool-length in the natural setting using well-controlled field experiments. Their finding that tools made by the crows to extract food from vertical holes on first visit were of a similar length regardless of hole depth is in contrast to findings from captive conspecifics. Kacelnik's group at Oxford University found that their birds matched tool length to distance-to-food and made tools to diameters that tracked the hole size. In this issue (Weir and Kacelnik 2006), they supported their previous claims that New Caledonian crows are able to chose tools according to the anticipation of their future actions by examining one bird's ("Betty") demonstration of spontaneous wire-bending and using it as a hook. The authors make the strong claim that the details of her behavior suggest a level of understanding of physical tasks that exceeds that previously attained by any other non-human subject, including apes. They argue that immediate causal inference might have been involved in Betty's wire-bending, but that sufficient experience plus swift generalizations would suffice for a sensitivity to tool dimensions. The difficult matter of distinguishing between causal understanding and associative learning processes is further examined in a paper by Huber and Gajdon (2006) reviewing experiments with skillful manipulative birds that do not use tools in the wild. Keas demonstrated the understanding of some functional aspects of a food container through mere observation and found an immediate solution in the string-pulling task, a well-probed test for means-end comprehension. In general, the solving of novel problems without recourse to trial-and-error learning may count as example of the appreciation of mechanical causation.

Ravens have also proved to understand physical causation in interactions with inanimate objects (e.g., Bugnyar and Heinrich 2006), but seem also gifted to form representations of mental causation in the social realm. In the third part we therefore deal with social logic. Bugnyar and Heinrich (2006) describe the tactics of ravens when storing or pilfering food to examine the possibility that ravens are capable of withholding intentions and providing false information (tactical deception). Such flexible deceptive tactics for social manipulation have been reported mainly for primates and used as example for theory of mind abilities in animals. Two papers are concerned with cognitive mechanisms of social learning, of which imitation has been commonly regarded as the most sophisticated form. Zentall (2006) provides a theoretical analysis of imitation, describes procedures that are capable of separating opaque imitation from other forms of social learning, and discusses claims that true imitation involves some degree of intentionality and goal directedness. Topal et al. (2006) concentrate on an advanced form of imitation (generalized imitation) showing that a dog can learn the general concept of imitation by understanding an action sequence on the basis of spontaneous observation alone, in terms of the initial state, the means, and the goal.

In the final part of the issue we deal with inferential logics. Here the authors will come close to what philosophers, linguists, and mathematicians consider as relevant to human logic. Pepperberg takes as one highly appropriate example of Grey parrots' intelligence recent demonstrations of their numerical competence (Pepperberg 2006). In addition to quantifying sets of up to and including six items using vocal English labels, to comprehend these labels fully and to have a zero-like concept, the famous individual "Alex" now also starts summing small quantities. These demonstrations imply that he understands number symbols as abstract representations of real-world collections, and that his sense of number compares favorably to that of chimpanzees and young human children. As Pepperberg recently argued, "the data for Alex suggest that a nonhuman, non-primate, non-mammalian has abilities that in an ape would be taken to indicate human competence" (Pepperberg 2002, p. 250). Moreover, his abilities contribute well to the recent reports of avian intelligence, which suggest that corvids and parrots are cognitively superior to other birds, and in many cases even apes (reviewed in Emery and Clayton 2004). Call (2006a) concentrates on another apparent aspect of logic, inferential reasoning. Based on recent experiments with chimpanzees, gorillas, orangutans, and bonobos, he argues that subjects reason and use logical operations based on inference by exclusion to locate hidden food. Several studies have shown that apes seem to be quite good at understanding and reasoning about certain physical properties of their world while at the same time being quite bad at associating arbitrary stimuli and responses (Call 2006b). Nevertheless, acquiring the capacities to reason or think "logically" in order to solve problems in their physical or social world more efficiently does not mean that subjects would lose their capacity to use associative processes or even rules of thumb. But the same is true for us humans.

Acknowledgments We thank Dr. Eiichi Izawa for his help with managing the symposium and with editing the special issue.

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