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REVIEW

Technical intelligence in animals: the kea model

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Abstract The ability to act on information flexibly is one of the cornerstones of intelligent behavior. As particularly informative example, tool-oriented behavior has been investigated to determine to which extent nonhuman animals understand means–end relations, object affordances, and have specific motor skills. Even planning with foresight, goal-directed problem solving and immediate causal inference have been a focus of research. However, these cognitive abilities may not be restricted to tool-using animals but may be found also in animals that show high levels of curiosity, object exploration and manipulation, and extractive foraging behavior. The kea, a New Zealand parrot, is a particularly good example. We here review findings from laboratory experiments and field observations of keas revealing surprising cognitive capacities in the physical domain. In an experiment with captive keas, the success rate of individuals that were allowed to observe a trained conspecific was significantly higher than that of naive control subjects due to their acquisition of some functional understanding of the task through observation. In a further experiment using the string-pulling task, a well-probed test for means–end comprehension, we found the keas finding an immediate solution that could not be improved upon in nine further trials. We interpreted their performance as insightful in the sense of being sensitive of the relevant functional properties of the task and thereby producing a new adaptive response without trial-and-error learning. Together, these findings contribute to the ongoing debate on the distribution of higher cognitive skills in the animal kingdom by showing high levels of sensorimotor intelligence in animals that do not use tools. In conclusion, we suggest that the 'Technical intelligence hypothesis' (Byrne, Machiavellian intelligence II: extensions and evaluations, pp 289–211, 1997), which has been proposed to explain the origin of the ape/monkey grade-shift in intelligence by a selection pressure upon an increased efficiency in foraging behavior, should be extended, that is, applied to some birds as well.

Keywords Technical intelligence · Sensorimotor Development · Social learning · Causal reasoning · Insight

Introduction

Alex and Betty, a Grey parrot and a New Caledonian crow, have received public attention as famous representatives of the top liga for cognitive abilities in birds (Pepperberg 1999; Weir et al. 2002). Reports of their preeminent performance in various challenging cognitive tasks that rival many nonhuman primates in understanding their physical and social worlds have fuelled the debate about the evolution of intelligence (Emery and Clayton 2004). Convergent evidence comes from neurobiologists, realizing a relatively large and well-developed avian pallium that processes information in a similar manner to mammalian sensory and motor cortices (The Avian Brain Nomenclature Consortium 2005). Together, these developments set the

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stage for a re-evaluation of the cognitive abilities of birds by challenging the hypothesis that intelligence is necessarily tied to language (Watanabe and Huber 2006; but see also the papers by Bugnyar and Heinrich, Hunt et al., Pepperberg, and Weir and Kacelnik, in the special issue "Animal logics").

One of the cognitive tools that are especially adaptive to solving the most important environmental problems in nature is *causal reasoning* (Visalberghi and Tomasello 1998; Lefebvre 2000; Lefebvre et al 2004; Emery and Clayton 2004; Hunt et al. 2006; Weir and Kacelnik 2006). Obviously, much of the adaptive behavior in animals depends on learning about recurrent sequences of events in their physical or social environments. A full-fledged, human capacity of causal reasoning might be characterized in terms of the construction of representations of event sequences in which one event is understood to bring about another event through the transmission of force or some other generative process (Sperber et al. 1995). Emphasis is laid upon the ability to understand not only events as being related in space and time but that there is some mediating force that allows the subjects to predict or control those events. The big question is whether animals adopt such 'explanatory attitudes' towards the physical or social world to come to an understanding of their underlying causal structure.

For many decades, researchers have tried to get a glimpse into the 'folk physics' of animals, i.e., their common sense understanding of *how* the world works, as well as *why* it works in the way it does (Köhler 1921; Povinelli 2000). However, despite many attempts in recent years, we are far from a common agreement of what animals really understand when they are engaged in object manipulations and other forms of modifying the environment for their own sake (see, for instance, the disagreement on the strategies used to solve tool-length tasks in New Caledonian crows; Hunt et al. 2006; Weir and Kacelnik 2006). Some researchers believe that it is not only humans but also many large-brained animals that develop an increasing ability to understand causal relationships on accumulating experience, with language being only a powerful accelerator of this process rather than a prerequisite (Hauser 2000; Rumbaugh et al. 2000). Others take a far more cautious position and warn not to over-interpret the animal's apprehension of cause–effect relations underlying tool use and complex object manipulation (Tomasello and Call 1997; Visalberghi and Tomasello 1998; Heyes 1998; Povinelli 2000).

Causal reasoning is only one way of achieving causal knowledge, and nature seems to have evolved alternatives. Associative learning among contiguous events is a very general and powerful mechanism, but is restricted to effects that immediately follow causes. Strong causal knowledge, i.e., the knowledge of causal connections among noncontiguous events, can either be generated by evolved programs that encode one class of important events as the probable or certain cause of another class (Kummer 1995). Alternatively, in the absence of such genetic programs, or in addition to them, causal reasoning is a means of detecting causal links between important events separated in space and time. It requires assigning cause–effect or means–end relationships to the physical or social world through either observation or insight. Such causal relationships between objects might result in the representation of abstract concepts, like "connectivity" (Hauser 1997), or in the construction of a chain of responses that lead to a goal.

In the remaining of this paper, we will try to fill this theoretical framework with concrete data from our kea research and then discuss the implications of these findings. First, we will review data that we collected in the recent past by studying keas that we confronted with challenging technical problems. The performance in those tasks allowed us to make inferences about which perceptual-motor abilities and which cognitive strategies have been involved. We then use these findings to suggest a re-evaluation of *insight* in animals as an intermediate step between "weak" and "strong" causal reasoning *sensu* Kummer (1995). In order to explain the striking difference in performance on various problem-solving tasks between laboratory-trained keas and their wild conspecifics, we will discuss the effect of humans and their artifacts on their cognitive development. Using Piaget's (1936) theory as framework, we then suggest that the kea's cognitive development is characterized by the interplay between sensorimotor intelligence and observational learning. Finally, we will conclude by suggesting an extension of the 'Technical intelligence hypothesis' (Byrne 1997) as an explanation for the evolution of cognition in keas.

Studying an unusual species: the kea

Kea (*Nestor notabilis*) are parrots endemic to New Zealand, where they breed high in the alpine environment of the Southern Alps. They have received public attention not only because of their strange ecology but also their reported playfulness and curiosity (for a comprehensive survey of this bird's evolution, ecology and behavior see Diamond and Bond 1999). Being bold, curious, and ingeniously destructive, their foraging is a wholly open and opportunistic process, trying everything and keeping what works. Instead of conquering new habitats, as it is characteristic of other curious birds, like ravens, opportunistic foraging has enabled the kea to have an extremely variable omnivorous diet, feeding on more than 100 species of plants, complemented by insects, eggs, shearwater chicks, and carcasses. Perhaps this is the reason why keas survived the mass destruction wrought by human settlement, while a large number of species including ravens were forced into extinction. Even the devastating impact on New Zealand's flora and fauna by the introduction of huge numbers of sheep was turned into an advantage by keas by firstly feeding on sheep carcasses and eventually attacking live sheep to obtain highly nutritious parts from the fatty tissue and the kidney.

Foraging is not only opportunistic and innovative but also highly extractive or, when human artifacts are involved, massively destructive. Keas scratch along the surface of objects with the tip of their bill, they draw the edge of the maxilla forcefully over the surface of an object or substrate to peal off parts, or hook the maxilla onto an object and scrap off small parts with the mandible, they push objects with the head, and tear with the bill. They open stems of herbs to feed on the core, dig in the ground for roots, and turn stones over in the alpine grassland in order to get access to insect larvae. Compared to other species of parrots, the bill of the kea seems to be well adapted for such ground foraging in a rocky habitat. It is better for probing small crevices (and also flowers for nectar) and prying objects rather than crushing them. Levering and pushing are common behavioral traits of object manipulation. When gravel is removed from the ground while digging, items are picked up with the bill and let go with a quick lateral movement of the head, so that the item is thrown for some distance (rummage).

Besides this adaptive and innovative foraging behavior, keas show a variety of social behaviors. Most fascinating is their huge repertoire of plays, their diversity of social strategies across age classes, and their complex dominance hierarchy, all culminating in the social manipulation of cooperation (Tebbich et al. 1996). This ape-like combination of extractive foraging, high sociality, extreme behavioral flexibility, and delayed maturation and lenience by adults towards the young seemed to us ideal prerequisites for the study of social and physical cognition in nonhuman animals. Finally, experiments done with captive keas at the Konrad Lorenz Institute for Ethology in Vienna proved that this species is an extremely appropriate model for aviary experiments, as they totally lack neophobia and are always eager to participate in instrumental tasks.

Learning the affordances of locking devices by observation

In many cases, animals are not able to eat the food in its natural form and have to perform some specific actions to obtain the edible parts. Apart from using tools to get access to the edible items (Beck 1980), animals often use special handling techniques like, e.g., gorillas (*Gorilla gorilla*) when removing the stings of some plants (Byrne 1997). In terms of time and energy, opening embedded food is a costly activity. Therefore, the rapid acquisition of food processing techniques by observation of skilled conspecifics conveys functional advantage.

In our studies, the keas' task was to open the lid of a large box that was fixed to its frame by numerous tricky locking devices (Huber et al. 2001). This task was adapted from Whiten et al.'s (1996) 'artificial fruit' for chimpanzees by functionally mimicking a resource that needed various types of manipulations to open it and extract an edible or otherwise attractive core. The manipulations necessary to dismantle the devices involved twisting a screw, forcefully removing a metal stick, and poking a bolt out of rings. The experiment was conducted in a big outdoor aviary where the siblings are kept with each other since they were 6 months old. Using the method of stepwise approximation, two males received training to the task of opening the apparatus. These birds were used as models after they became proficient. We allowed five 'observers' to watch the model for about 200 min within three consecutive days, thereby observing about 50 complete openings of the model. They were then tested individually on three consecutive days. Tests were also made with five 'nonobservers', who were completely naive to the task.

Altogether, the results provide strong evidence for social effects on object exploration and problem-solving behavior in keas. The five observers showed in comparison with the nonobservers (1) faster approach to the locking devices, (2) extended persistence in their manipulative actions, (3) relatively more tactile exploration, and (4) greater success in opening the locking devices. We interpreted the social effects on approach and manipulation persistence in terms of social facilitation and stimulus enhancement. The kea's innate preference for object play and exploration has been 'energized' by the observation of the model's activity (Clayton 1978), and their attention has been drawn to the locus or the object at which the model executed highly salient manipulations (Thorpe 1956). However, stimulus enhancement could not explain why, for instance, the observers but not the nonobservers pulled the split pin out. The observers–in comparison to nonobservers–neither prefer the 'correct' part of the split pin (the loop end) nor manipulate it longer (see Table 2 in Huber et al. 2001). Also, the comparison of the test performance of the most successful birds in each group showed that the observer's success at the split pin could not be explained by focusing at it from the beginning and then responding to it in the most natural way, namely by pulling (see Table 4 in Huber et al. 2001). Therefore, and given the striking advantage of observers relative to nonobservers with regard to opening the locking devices–observers opened five times as many devices than did the nonobservers, and one observer opened all three devices within the first 2 min of the test–Huber et al. (2001) concluded that the keas learned something during observation. However, they copied neither the details of the opening technique shown by the models, as, for instance, marmosets did in our laboratory (Voelkl and Huber 2000) nor the sequence of actions required to open the three locking devices.

From their observations of foraging behavior in free-living keas, Diamond and Bond (1999) concluded that this species does not need to learn novel foraging techniques by imitation. When they do use a technique that they have observed, it is generally a simple movement, such as overturning a rock, that is well within their competence and that they had probably often performed before. Juveniles and fledglings may learn the appearance of food and its location through observing others, but they do not perform the particular actions of the foraging adult. They are drawn to the objects of adult interest, but once in possession of such an item, they appear to approach the task of dismantling and consuming it without socially mediated preconceptions. "They are guided more by the affordances of the object than by the behavior of other individuals" (Diamond and Bond 1999, p 98).

Generally, it may be a characteristic of explorative and playful animals to employ their own, idiosyncratic methods to manipulate attractive objects. Slavish copying might either be a valuable alternative in the absence of insight (Huber 1998) or used as a means of copying the other's goal in a social game, as it is evidenced by human children (Want and Harris 2002). But it does not seem to be the most efficient strategy in foraging or manipulative problem solving. The important type of information provided by the skilful model is therefore not *how* to do but *what* to do, i.e., what is *functional* in the given situation. Having seen an object used in some way, the observer knows that this functional use is *possible* for this sort of object (e.g., 'the white screw can be removed') and applies its own behavioral strategies. Based on the observations of chimpanzees in a social learning task (Tomasello et al. 1987), Tomasello (1996) used the term *emulation* to describe this apparently intelligent form of observational learning. Further elaboration has generated a differentiation of information involved, ranging from simple 'static' object properties to 'dynamic' object relationships to physical concepts (Byrne 1998; Want and Harris 2002; Whiten et al. 2004; Huber in press).

In the case of keas, Huber and co-authors suggested that these birds are able to acquire very specific information about the *function* or the potential use of the locking devices (Huber et al. 2001). Rather than learning that the split pin, for instance, is a signal for food, or is attractive as a manipulandum, or has an attractive loop end, the observer has learnt that the split pin '*can be pulled out*.' The nonobservers, which have never seen the split pin pulled out, or in a remote position from the screw, were not prepared to pull at the split pin forcefully (but pulled at it weakly at least as often than observers). Note that only when some force (about 1 N) is applied to the split pin with its forked shape (Fig. 1a), it starts to move. Thus, the crucial information that put the observers into a significant advantage over the nonobservers was the observed *affordance* of the locking devices, i.e., the dynamic relationship between the fixed and the movable parts of the steel box. This knowledge has dictated the initial actions of the observers at test, which seemed goal-directed rather than explorative, whereas the nonobservers spent much time in exploring the locking devices before probing the whole repertoire of demolition actions. Support for this explanation in terms of goal-directed actions developed by learning the affordances of objects through observation comes from subsequent tests of means–end behavior in captive keas.

String-pulling performance as example of insight?

Means–end behavior involves the deliberate and planned execution of a sequence of steps to achieve a goal and occurs in situations where an obstacle preventing the achievement of the goal must initially be removed (Piaget 1936; Willatts 1999). The 'obstacle' in the case of the string-pulling task, which involves the presentation of food suspended by a string fixed on a perch, not accessible from the ground or from flight, is the distance between the subject' position on the perch and the desired food item. In order to overcome this distance and to obtain the food, a bird needs not only to coordinate its bill and foot using fine-tuned motor skills but also to execute a precise sequence of several different steps repeated in that same sequence several times before the food is reached. Known since ancient times (e.g., Plinius), many experiments testing birds' ability to use a physical object to obtain food that is out of reach has involved the string-pulling task (reviews in Vince 1961; Dücker and Rensch 1997; Seibt and Wickler 2006). In contrast, following Köhler's (1921) famous studies with chimpanzees on Teneriffa island, primates and other mammals have been tested with horizontal strings in order to test their ability to access food that is out of reach. Here, pulling the food into reach does not require coordinated movements and thus their attempts to reach the food may have only resulted in manipulating its vicinity.

After a series of studies with great tits (*Parus major*), greenfinches (*Carduelis chloris*), canaries (*Serinus*), and chaffinches (*Fringilla coelebs*) of various ages, Vince (1961) suggested that the performance is based on trial-and-error learning. Success tends to occur intermittently and the improvement in performance is, on the whole, gradual. When presented with different patterns of two-string problems, budgerigars (*Melopsittacus undulatus*) solved only two out of eight spontaneously, while an Indian starling (*Acridotheres tristis*) and a jackdaw (*Corvus monedula*) failed to solve any of the problems (Dücker and Rensch 1977). Very recently, Seibt and Wickler (2006) tested large numbers of goldfinches (*Carduelis carduelis*) and siskins (*C. spinus*) with the string-pulling task and found considerable inter-individual differences in performance. Only 23% of the goldfinches ($N = 52$) managed to solve the task themselves, 25% succeeded after seeing a skilful conspecific, but 52% failed either way. In siskins ($N = 29$), the respective proportions were 62, 10, and 28%.

Fig. 1 A series of snapshots showing keas **a** opening the split pin of the artificial fruit (Huber et al. 2001); **b** pulling the string to obtain the attached food reward (Werdenich and Huber 2006); **c** climbing up a rode and pushing the tube to obtain the butter smeared into its inner part (Gajdon et al. 2004); and **d** lifting the lid of a rubbish bin to get access to the remainings of a hotel kitchen (Gajdon et al. 2006)

Goal-directed solutions would require a bird showing the pull/step-solution spontaneously, with the complete act being accomplished in a rapid and smooth manner with the entire absence of fumbling (Thorpe 1956). Because the string constitutes a physical connection to an out-of-reach object of desire, the solution to the problem could in principle be perceived directly. However, out of more than 15 species of birds tested with the string-pulling task, only ravens were credited to understand the cause–effect relationship between food, string and perch, to use effective techniques instantaneously, and to generalize the solution to various different situations (Heinrich 1995, 2000; Heinrich and Bugnyar 2005).

The young keas at the Konrad Lorenz Institute in Vienna had no string-pulling experience when we started to test them on such problems (Werdenich and Huber 2006). The apparatus consisted of a horizontal wooden perch (170 cm in length) that was carried by two poles (170 cm in height). In the initial task, they were required to pull up a baited object hanging from a 70 cm long string (Fig. 1b) thus providing no direct access to it.

The keas were highly motivated to get the reward and the majority of them demonstrated exceptional performance. With the exception of the fledgling, the keas solved the string-pulling task by coordinating bill and a foot in their first trial. Within few (<15) seconds of their first attempt, four of the remaining six keas showed the most effective and intelligent solution to this problem. These individuals immediately perched above the string with food, then reached down, grasped the string with their bill, and pulled the baited string up. The birds appeared to have achieved these effective solutions spontaneously because the complete act was accomplished in a rapid and straightforward manner. They were not showing any exploratory or insufficient methods like flying up from the ground or pecking at the string, as seen in ravens (see Heinrich and Bugnyar 2005). With the possible exception[1] of two Grey parrots (Pepperberg 2004), this is the quickest manner in which the string-pulling problem had been solved by birds including ravens (Heinrich and Bugnyar 2005) and kakarikis (Funk 2002). Perhaps the keas found a solution to the retrieval problem *before* their first tryout.

It was even more remarkable that from the first trial of the initial string-pulling task onwards there was no significant improvement of the group across the test. Neither the time of completion nor the number of pullings or drops decreased in the whole bird sample in a significant manner. In contrast, in all other birds tested so far–including ravens (Heinrich 1995;

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[1] A direct comparison is not possible because of the lack of first trial measurements of the performance of the Grey parrots. Pepperberg (2004) only reported that two birds immediately performed and correctly repeated the targeted action each time without any hesitation, although the actions were not necessarily performed smoothly.

Heinrich and Bugnyar 2005)–improvement of performance was, on the whole, gradual and intermittent. As the application of an innate string-pulling response by the keas is very unlikely, as the birds used up to seven different techniques, the overt construction, rather than the explicit training, of a sequence of actions in order to bring about an effect was the key achievement in the keas' string-pulling behavior. Interestingly, the keas remained quite flexible in using different techniques throughout the whole experiment, i.e., for about 180 trials. Although there was some evidence of an increase in the efficiency of particular action elements, the keas did not eliminate techniques. The elimination of methods in keas is perhaps hampered by their strong inclination towards object exploration and object play. Nevertheless, as is evident from the short task completion times, the majority of their actions were food-directed and guided by some understanding of the key functional features or affordances of the task. The results are consistent with the hypothesis derived from the performance of ravens (Heinrich 2000) that the birds anticipate consequences of some novel motor patterns before committing them to action.

Although the execution of the involved motor acts rests on preprogrammed action elements, the real challenge in the string-pulling task is the assembling of the actions into a coherent whole. Only the fledgling was not able to coordinate the activities of bill and feet when being tested at 7 months of age but succeeded 1 month later. Perhaps the collection of the necessary proprioceptive experiences is a necessary, though not sufficient, precondition for the construction of an action sequence that is appropriate for the string-pulling task.

After the basic test, we introduced further tests in which the birds were required to choose among different strings, of which only one held a reward. In these tests, we used different rewards and colors for the strings, a string with an overload, and strings in complex spatial relationships. We wanted to assess whether the keas' choice of the correct string is spontaneous or acquired by trial and error.

Again, the keas behaved very efficiently by showing high success rates in the discrimination tasks. They seemed to be attentive to the end of the strings and to trace the paths of the strings. The two-string choice experiments showed that the birds instantaneously distinguished between strings with baited and unbaited objects; only two of seven subjects failed in the first trial, but none in the following two trials. In terms of first-choice performance, such immediate solutions were not achieved in the crossed strings tasks. Only one bird chose the correct string in the first trial but made only two more errors in the 29 following trials. Three birds learned quickly after the failure in the first trial, with only five or six more errors in the 29 following trials. Only two birds remained at chance level first but were overwhelmingly correct thereafter (with a minimum of 26 correct trials out of 30).

Note, however, that except for one raven in Heinrich's study (1995), to our knowledge, there are no reports of birds solving this problem at all. Even for primates, the solution is not always immediate and may require an extended period of learning (Tomasello and Call 1997; Povinelli 2000). And compared to dogs, rats and cats, the keas' performance is quite surprising. Although first trained on some 20 trials to discriminate between a baited and a nonbaited string, dogs were not reliably successful at pulling the baited string first on test (Osthaus et al. 2005). Furthermore, they paw at the string whose proximal end is close to the food, thereby showing the proximity error (a similar error has been reported for tamarins in both the horizontal (Santos et al. 1999) and the vertical plane (Hood et al. 1999)). And when facing two crossed strings, performance remained below chance level across 20 trials.

The most advanced solution in the crossed and slanted strings tasks would require the possession of a concept of *connectedness* (Piaget 1936). However, without presenting strings in probe trials that vary in the visual salience of connectedness, to what extent an understanding of *contact* is grounded in a genuine appreciation of physical *connection* (Hauser 1997; Povinelli 2000) remains unclear. A less advanced, though equally effective, solution would require attendance to the perceptually tangible cues of the strings, particularly the *continuity* of the paths, as opposed to causally imperceptible physical factors. But tracing the paths of the strings is difficult when facing a crossing at some distance. The much better performance in the slanted strings task than in the crossed strings task (only one kea failed in the first trial; the whole group chose the correct string in 87% of the cases) might be counted as evidence that tracing the paths of the strings was indeed the critical element in the keas' discrimination performance. We therefore submit that keas solve the string-pulling problem by virtue of means–end understanding.

It is interesting to compare the results of Werdenich and Huber (2006) with those of Johnston (1999) investigating string pulling in wild keas. From a total of 19 keas tested, 6 solved the problem in their first trial. Although the presence of conspecifics and the vicinity of a ski field might have negatively affected their performance, the significantly better performance of the captive keas in the same task might be primarily a result of higher amounts of stimulation and experience during ontogeny. We will discuss the accelerating effects of human rearing later, but first provide further empirical support from two field studies conducted by us.

The tube removal task

This task was invented by us in order to allow a fair comparison between captive and free-living keas. For the task to be counted as a success, a tube has to be removed from an upright pole (Fig. 1c). This conspicuous behavior is easily seen from great distance even in field conditions. As a reward, we used butter smeared between the inner and outer layer of a tube. Only when the tube was removed from the pole, the inner and outer part of the tube fell apart giving full access to the reward. The pole was so long that an individual could not complete the task by pushing the tube up with its bill. Instead, the bird was required to climb onto the pole and push the tube up the pole with its bill at the same time. We thought that the most challenging aspect of the task is to bring an object into the appropriate position in relation to another.

Before we started with the field experiments (Gajdon et al. 2004), we presented the apparatus to visually separated captive keas in Vienna. Two of them removed the tube in the first session and other two in the third and fourth sessions, respectively. Two birds that failed to do so within a few trials were given some demonstration and succeeded after three and nine demonstrations, respectively. In order to test whether the birds removed tubes so quickly because they were aware about the interrelation of pole end and tube removal, an apparatus with two poles was provided. A blue stick added vertically or horizontally at pole ends prevented the removal of tube from one pole. All six birds immediately removed the tube from the appropriate pole with the vertical stick in five successive trials. However, they only did so when playful tube lifting was prevented by adding a small rectangular board as blocker at one of two poles in previous sessions. In sum, the captive keas showed that the solution of this task is well within the species capacity.

When we presented the one-pole apparatus to free-living keas in Mt. Cook National Park, the birds showed immediate interest in the tube, which they manipulated with great patience. In most cases, such investigative behaviors were observed by several conspecifics in the vicinity. Nevertheless, only one naive bird managed to remove a tube twice in 25 half-hour sessions (baseline). Due to reasons unrelated to the experiment, this bird disappeared right after its second success in session 8 and no other bird solved the task. Therefore, we trained one bird to remove tubes in visual isolation from other keas and subsequently used him as demonstrator for others. Even under such facilitative conditions, only 2 of at least 11 birds started to remove tubes during 28 sessions (demonstration phase).

Why did most of the keas fail in this study? Although unsuccessful birds put their feet significantly more often on the pole during the demonstration phase than during the baseline phase, they failed to climb with the tube on the pole. Neither relative duration spent moving the tube nor climbing duration was different between baseline and demonstration phase. We concluded that wild keas were unable to learn the affordances of the task or to copy the necessary technique in its entirety. To examine if this failure to benefit from skilled conspecifics was due to the specific task, we sought to find a naturally occurring case of extractive group foraging.

Rubbish bin opening

Outside the kitchen of a large multi-storey hotel in Mount Cook Village, we found keas opening the lids of rubbish bins during night and in the early morning (Fig. 1d). The hotel staff has witnessed this behavior for several years. It caught our attention because opening of the lids of 120 L rubbish bins for food scraps within seemed to us an ideal example of innovative behavior (Gajdon et al. 2006). We were interested to which extent this innovative technique was learned socially and spread in the local population. Interestingly, only 5 of 36 individually recognized birds in the area of the bins succeeded in opening the lids. Another 17 birds were seen to scrounge but were never observed to open a bin completely. Scrounging, however, could not account for their failures because bin-openers had a better payoff than scroungers in terms of amount and quality of food. We were also unable to find evidence for an explanation in terms of low access rates to closed bins by unsuccessful birds. Rather, two thirds of those birds frequently attempted to open the bins but failed to find the trick. Due to the big size of the lids, the keas are unable to lift the lid up to its upright position from which it starts to drop backwards, without making a few steps toward the hinge during lifting. It seems that except for few innovators, the birds have not grasped the key affordance of the task given by the spatial relationship between lid and bin. Would slavish copying of bin opening behavior be a last resort in the lack of insight?

Two bin-openers, aged 15 and 17 years, at least were much more efficient in bin opening than openers of 3 and 4 years of age: Their proportion of the number of successful attempts was about 12 times higher. This indicates that a lot of individual learning is required for acquisition of this technique and that social learning did play a minor role to achieve it, despite their opportunities to watch successful bin opening.

Thus, we come to the similar conclusion as in tube-removal task that wild keas seem to have difficulties solving tasks in which they have to consider the position of an object in relation to another (pole end or hinge). One reason for this behavior might be that natural foraging tasks do not require this. Alternatively, kea captive husbandry provides the birds with many demonstrations of complicated object manipulation such as raking food remaining in a shovel and then putting them in a basket, etc. Also, the birds participated in some patterned string-pulling tasks described earlier. Thus, some enculturation-like effects may play a role in the difference indicated earlier.

Cognitive development

When keas face a difficult technical problem, they show quite striking differences in performance, depending on whether they are tested in the wild or in captivity. Captive keas appeared not only to be far more clever and skilled but also able to use socially provided information much more intensively or effectively. Of course, we have to take into account a number of inhibitory effects on performance arising from testing in the wild, however we nevertheless believe that the crucial difference in performance will be found in the cognitive development of the animals.

Extensive interactions with humans can potentiate some human-like social and cognitive skills in animals that their wild counterparts do not seem to possess (Tomasello et al. 1993; Call and Tomasello 1996). The captive young keas in Vienna are kept in a large aviary, where they are permanently confronted with tricky laboratory tasks and with high numbers of toys and other human artifacts. When the fledglings are introduced in this aviary, they are not only in a highly investigative environment but also permanently interacting with highly experienced group members. In this technical atmosphere, they start out to learn about not only their effects on the environment but functional relationships between objects and thus acquire rapidly a high degree of manipulative skill. Based on Piaget's (1936) theory of cognitive development in humans[2], we propose that in keas, the interaction with their environment leads not only to a simple increase in number of experiences from which to generalize but more importantly to the development of an *intermediate* causal understanding that incorporates physical relationships.

We may describe this development as a continuous move from learning to reasoning, i.e., from associating a perceivable and an imagined (i.e., perceptually not available) event instead of associating two perceivable events (Premack 1995; Call 2004). The specific advantage of Piaget's (1936) theory over models that simply contrast learning and reasoning (like Premack 1995) is that it proposes a smooth transition from acting on external events to acting on internal (mental) models that cover external regularities. It is based on the core idea that developmental stages are sequentially constructed and reconstructed at higher levels through *circular reactions*, i.e., through assimilation of experience to schemes and through accommodation of those schemes to experience. This development is not the result of an automatic execution of a genetic program but of the repeated exploration of properties of objects, space, time, and causality. The captive keas in Vienna have far more opportunities for such repeated exploration than their wild counterparts.

According to Piaget (1936), the sensorimotor development is characterized by three sequentially developed circular reactions. While the *primary* circular reactions are characterized by repeated actions on the self or on environmental objects that can be assimilated to simple schemes, the *secondary* circular reactions depend on voluntary prehension and involve repeated actions that aim at re-creating contingent effects on the environment. We frequently observed the juvenile captive keas performing actions aimed at reproducing interesting effects, like throwing food items into the water basin, then looking whether they float or dissolve or disappear. Floating items are then pushed in the same way that children do when playing with sailing boats. Keas have also been observed producing noise, then repeating this action or varying it somehow. When schemes become mobile and freely combinatory, the differentiation between actions that serve as means–like setting aside an obstacle–and the final actions–like grasping the object–emerges. The transition to the *tertiary* circular reactions occurs when the subject begins to explore new objects through serial application of its familiar schemes, thereby getting interested in the outcome of actions rather than in the actions themselves. These actions do not focus on relations between one's own action and an object but rather towards the relations among objects, e.g., by stacking them, by putting one inside another, or by using one as a tool to reach another. Whereas there is wide agreement that primates are able to show secondary circular reactions (see reviews in Antinucci 1989; Tomasello and Call 1997; Parker and McKinney 1999), the achievement of tertiary circular reactions is controversial (see comments in Chevalier-Skolnikoff 1989). Pulling at a string in order to secure the attached food might be counted as an evidence for tertiary schems. However, in contrast to children that search for a stick to retrieve desired objects, the keas were not required to combine string with food.

At about 18 months of age, human infants can imagine the relations and transformations of objects mentally, and thus they use mental manipulations or *insight*, rather than overt trial-and-error, to solve sensorimotor problems. Although there is a growing number of reports of nonhuman animals being able to achieve the sixth stage of object permanence–among them Grey parrots (Pepperberg et al. 1997) and marmosets (Mendes and Huber 2004)–which consists of the mental representation of sequential displacements of objects, it is far from obvious that this achievement is paralleled by the mental representation of simple causal relations or tertiary circular reactions. Intensified research on the ontogeny of sensorimotor intelligence in nonhuman animals is necessary to understand whether they are capable of building mental scenarios or not, so that alternative choices

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[2] Despite a number of caveats (see, for discussion, Doré and Dumas 1987; Parker and McKinney 1999; Pepperberg 1999, 2002) and criticism on the basis of two principal grounds, recapitulationism and anthropomorphism (Vauclair 1996), Piaget's theory and its application to animal cognition has many strengths and is well suited to address the general issue of the origin, nature, ontogeny, and function of animal as well as human knowledge (Doré and Dumas 1987; Vauclair 1999).

or motor patterns are expressed or suppressed depending on their probable outcome, either before or after such outcome has been experienced.

Thorpe (1956) proposed that *insight*, on the one hand, should be considered primarily as a matter of the organization of perceptions, leading to the apprehension of relations. *Insight learning*, on the other hand, includes as an essential element the appropriate organization of effector response, and can be defined as "the sudden production of a new adaptive response not arrived at by trial behaviour or the solution of a problem by the sudden adaptive reorganization of experience" (Thorpe 1956, p 100). This concept deviates from Piaget's, as it separates to some extent the perceptual and motor aspects of intelligence. But it remains to be proved if an animal could achieve any forms of insight passively, without being engaged in action.

A further interesting aspect of Piaget's model of cognitive development for the interpretation of the difference in performance between captive and wild keas is the relation between sensorimotor intelligence and observational learning. Piaget's model correlates different degrees and types of imitative ability with different stages of sensorimotor intellectual development. The capacity to copy actions already present in the subject's repertoire is characteristic of the fourth stage of the Imitation Series, regarded as running in parallel in time with the Sensorimotor Intelligence Series. The capacity to copy novel actions, that is to *imitate*, is characteristic of the fifth stage of the Imitation Series and is dependent upon the tertiary circular reactions in the fifth stage in the parallel Sensorimotor Series. Piaget clearly indicated that imitation is dependent on the development of intelligence, neither present from birth nor an independent capacity of lesser significance (see also Parker and Gibson 1977). In line with this conception, we might suggest that the ability of keas to learn by observation is also a matter of cognitive development, being to some degree dependent on their understanding of causal relationships in the inanimate world. The captive keas' ability to learn the affordances of the locking devices by observation in Huber et al. (2001), in contrast to the failures of wild keas to learn by observation the tube lifting (Gajdon et al. 2004) or the bin opening (Gajdon et al. 2006), provides evidence for this hypothesis. What remains to be learnt from the kea model of the interplay between technical and social intelligence is its evolutionary significance, i.e., why keas show these astonishing cognitive capacities but many other birds apparently do not.

The 'Extended' Technical intelligence hypothesis

For primates, numerous researchers proposed that problem-solving capacity is a correlate of having a complex social system and a long life (the 'Social function of intellect hypothesis'; Jolly 1966; Humphrey 1976). Marler (1996) suggested similar selection pressures for birds, and Pepperberg (1999) added emphasis on the combination of intelligence and advanced communication skills in parrots. Indeed, parrots and corvids may rival primates in not only relative brain and telencephalic volumes (Iwaniuk et al. 2005) but also some cognitive abilities (Emery and Clayton 2004).

Even in primates, the need to solve 'Machiavellian' problems in the social world might not be the only possible selective pressure for the evolution of intelligence. The 'Technical intelligence hypothesis' (Byrne 1997) has been advanced to explain the origin of the ape/monkey grade-shift in intelligence in terms of technical, mechanical selective pressures. The term has been used as banner for the collection of several partly-linked hypotheses put forward to explain increasing efficiency in foraging behavior as being more necessary for great apes than monkeys because of their large size, the difficulties of brachiation for distance travel, and their reliance on high-quality diet. It has not been proposed as an alternative to the 'Machiavellian intelligence hypothesis' (Byrne and Whiten 1988) but as a complement, with the latter being a much better explanation for the haplorhine rise in intelligence and the later hominid one that led to *Homo erectus* (Byrne 1997). We here submit that the 'Technical intelligence hypothesis' should be extended, namely by applying it to some birds as well.

The ability of some birds to use tools might be the primary candidate for investigating the validity of this extension of the original hypothesis. But as evidenced by some corvids and parrots, among them most obviously ravens, Grey parrots, and now also keas, it might not be the only phenomenon worth looking for special cognitive capacities related to sensorimotor intelligence. As pointed out by Byrne (1997), it is not the *fact* that animals use tools that is interesting or significant in itself, but the *manner* in which the tool is employed. On the one hand, tools might be used in quite simple ways, neither embedded in an elaborate organization of action nor being the result of an understanding of the causal relations involved (Visalberghi and Tomasello 1998). On the other hand, the ability to understand functional properties of objects, ranging from simple static relationships to complex dynamic ones, and the ability to coordinate actions accordingly have been demonstrated by animals in other ways of foraging than by tool using. Parker and Gibson (1977) emphasized that concealed and hard-to-extract food create special problems to animals that lack specialized anatomy to do so. Advanced forms of sensorimotor intelligence are required, especially, when the need to forage extractively arises seasonally and over a wide range of foods . "We believe that *tertiary sensorimotor intelligence* was favored in situations of locally variable limited seasonal availability of embedded or encased high protein foods susceptible to extractive foraging and feeding with the aid of trial and error object–object manipulations based on an understanding of causality. Once intelligence evolved, it would allow broad application of *complex object manipulation* schemata" (Parker and Gibson 1977, p 637).

All those ingredients for a selective scenario for the evolution of sensorimotor intelligence in primates applies to the kea as well. The only difference to the tool-using primates, for which the extractive-foraging hypothesis has been advanced, is that the skilled feeding techniques do not involve tools as defined by "the external employment of unattached environmental objects to alter more efficiently the form, position, or condition of another object" (Beck 1980, p 10). Perhaps, having the equivalent of a Swiss Army knife (i.e., their beak) attached permanently to their body may render the need for tool construction less important for parrots. In this sense, the technical intelligence hypothesis needs again to be extended, this time to include *tertiary sensorimotor intelligence* in the absence of tool use and manipulation. The findings from the kea studies have shown that neither extensive tool use and manufacturing, like in New Caledonian crows (*Corvus moneduloides*; Weir et al. 2002) nor food caching and feeding in the vicinity of dangerous predators, like in ravens (Bugnyar and Kotrschal 2002; Bugnyar and Heinrich 2006), are necessary or sufficient for advanced technical intelligence in birds.

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