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Rationality

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Definitions

Rational

To be *rational* means to reason based on logic (see [Logic](#)). This definition of rationality is agnostic with respect to physical mechanism, and as a result allows for descriptions of both biological organisms and computing machines as being rational, if their behavior is governed by logic. For an excellent discussion of reasoning in both humans and animals, see the edited volumes by Hurley and Nudds (2006) and Watanabe et al. (2009) from which this work heavily draws. Rational behavior can also be considered to be *optimal* or *ideal*. The behavior of a living organism can therefore be compared to a model designed according to principles of rationality, such as optimal foraging theory (Stephens and Krebs 1986), ideal observer models of perception (Liu et al. 1995), rational accounts of causality (Cheng 1997; Waldmann et al. 2006, 2008), and Bayesian approaches to decision-making (Holyoak and Cheng 2011; Lu et al. 2008; Oaksford and Chater 2007). The remainder of

this entry will focus exclusively on psychological rationality (i.e., reasoning and logic) and not rationality by functional rationality.

Logic

Logic describes the rules or principles by which a conclusion is validly derived from its premises. A logical inference involves the use of logical rules or principles by which a conclusion is validly derived from premises. A hallmark of a logical inference is that it allows new knowledge to be inferred rather than acquired through direct experience (Watanabe and Huber 2006).

Top-Down

Rational processes are often characterized as being top-down, in contrast to bottom-up processes such as associative learning and conditioning. Top-down processes are rational because they involve the individual going beyond prior experience to derive knowledge or base decisions on the principles of logic. Some examples to be covered below involve rats or pigeons making inferences about the temporal, spatial, or causal relations between events that had never been directly experienced together. These types of inference can be derived from coherent and connected representations (aka cognitive maps, Blaisdell 2009; Tolman 1948) that integrate prior direct experiences, such as prior learning of an A–B and a B–C relationship. The integrated A–B–C map provides the

structure upon which A–C relationships may be logically computed (further details below).

Related to the concept of top-down processing is the concept of an informational approach to learning and behavior. These approaches range from early work conceptualizing animal behavior as hypothesis testing (Krechevsky 1932), to recent accounts in terms of propositional knowledge (De Houwer 2009) and information theory (Gallistel and Gibbon 2000; Gallistel et al. 2001).

Reasoning

Reasoning is the process of behaving following principles of logic and rationality. Most descriptions and discussions of reasoning involve behavior that goes “beyond the information given” (Waldmann et al. 2006), in that the behavior was not previously directly learned through principles of reinforcement or reward, nor through other means of direct experience or observation, but instead through an extrapolation beyond the scope of prior learning.

Categories of Rationality

The following section catalogs the types of reasoning processes that reflect rationality in animals. Many of these concepts are derived from their use in the study of human rationality and reasoning and are necessarily anthropocentric in their origin. Nevertheless, there is no *a priori* basis for defining rationality as a strictly human behavioral trait, and the origins of many human-type cognitive processes often have deep evolutionary roots. Thus, homologous, or at least analogous, reasoning processes that lend themselves to rational analysis can be found in nonhuman animals (Blaisdell 2016).

Logical or Deductive Inference

The following section presents the six most common types of deductive logical inferences studied in animals. Such inferences are also called *deductive* because the conclusion is deduced from its premises. For example, if all swans are white, and you are told there is a swan in the pond, you can

deduce that it is white (cf. *inductive* inference in section [Induction](#)).

Stimulus Equivalence

Equivalence is a property that defines the relationship between stimuli. Stimulus equivalence was originally defined by Sidman (1990) and involves three types of relations between three stimuli (A, B, and C) that have appeared together in pairwise fashion (i.e., AB, and BC), such as during operant or Pavlovian conditioning, or through mere exposure. These relations are *reflexivity*, *symmetry*, and *transitivity*. In an operant matching procedure, for example, if the subject is reinforced for choosing B after A and C after B, called A–B and B–C matching, respectively, subjects will often match each stimulus to itself (A–A matching), which is called reflexivity. If subjects do the reverse of what was explicitly learned, choosing B after A or C after B, this is called symmetry. Finally, if the subject matches C to A, despite C and A never having appeared together before, this is called transitivity. Urcuioli (2008) has provided a theoretical account for these types of matching behavior in pigeons (see also Urcuioli 2015). Equivalence learning is thought to serve as the basis for equivalence class formation, by which multiple stimuli are grouped into the same category through sharing a common outcome or an equivalence relationship (Honey and Hall 1989).

The stimulus relation of transitivity deserves special mention due to its role in studying logical deductive inference in animals. A transitive relation need not involve equivalence. Rather, a transitive relationship could involve the ordinal relations between sets of paired stimuli. For example, when presented a choice between A and B, if choosing A but not B is always rewarded, and when presented with a choice between B and C, if choosing B but not C is always rewarded, then, when faced with a novel choice between A and C, a transitive inference would involve the choice of A over C. While A and C never had a history of comparison or differential reward with respect to each other directly, a transitive relationship of $A > B > C$ would result in a logical deduction that, if $A > B$ and $B > C$, therefore $A > C$. This

would be a highly useful behavior for an individual living in a social group with a dominance hierarchy. For example, if Individual C has previously observed Individual A always (or usually) win in competitions for a resource (food, mating opportunities, etc.) against Individual B, and Individual B always (or usually) win in competitions with the observing Individual C, Individual C would benefit from inferring that it would also lose in competition with Individual A despite having no previous competitive experience with A. This inference could certainly save Individual C the danger (or embarrassment) of losing a competition.

There has been much debate over the psychological mechanisms that underlie the transitive inference. While some have claimed evidence for a representational account in terms of encoding ordinal relations between stimuli (Bunsey and Eichenbaum 1996), others have found support for simpler associative accounts based on concepts such as value transfer (Frank et al. 2003; Zentall et al. 1996).

Spatial Deductive Inferences

Deductive inferences have been shown in the spatial domain. Perhaps the most primitive type of spatial inference is *dead reckoning* (short for deductive reckoning). Dead reckoning is the process of calculating one's current position by using a previously determined position and advancing that position based upon a known or estimated rate of movement through space over elapsed time. Many vertebrate and invertebrate species show evidence of using a *path integration* process to navigate by dead reckoning (Collett et al. 1998; Etienne et al. 1986). After making an outward journey from a home nest, with many twists and turns, the animal is able to navigate in more or less a direct line back to the home nest after encountering a food item. The spatial vector encoding the distance and direction from the animal's current location to its home nest is computed by integrating each segment of the journey and computing a vector between the current location and the starting point (home nest).

A second kind of deductive inference involves the calculation of the allocentric spatial

relationship, or vector, between two external points in space that have never previously been observed together, nor for which the animal has traveled directly from one to the other. According to the spatial integration hypothesis of *cognitive map* formation (Blaisdell 2009), complex spatial representations can be built by linking together simpler representations that share common elements. A spatial representation containing three events (A, B, and C) can be built in one of two ways. On the one hand, all three events could be presented simultaneously, in which case the animal could construct a spatial representation containing all three elements. For example, presenting landmarks (LMs) A and B together with a food goal could establish a spatial map containing all three elements. On the other hand, the same three-element spatial map could be constructed in a piecemeal fashion by joining together two simpler representations, each containing two of the three elements. This process would allow subjects to construct the same three-element map without experiencing all three elements at the same time. An integrated map allows the subject to compute novel relationships among map elements beyond direct experience; a hallmark of the cognitive map.

In Phase 1 of an experiment with pigeons (Sawa et al. 2005; see also Blaisdell and Cook 2005a), subjects received presentations of two visual landmarks consisting of colored geometric shapes (A and B) on a touchscreen in an operant chamber in Phase 1. The screen location of the pair of landmarks varied across trials, but they always bore the same spatial relationship to each other. Pigeons then received training in Phase 2 consisting of A→Goal pairings. The screen location of the goal was randomly determined from trial to trial. LM A maintained a stable spatial relationship to the goal, thereby signaling the goal location. After pigeons were reliably finding the goal in the presence of LM A, they received nonreinforced test trials with LM B alone. If pigeons had acquired the B→A map during Phase 1 and the A→Goal map during Phase 2, then they would be able to compute the B→Goal spatial relationship or map. Evidence for the B→Goal spatial inference was found in the

highest density of screen pecks being clustered at the inferred Goal location. Similar findings have been reported by Chamizo et al. 2006 and Leising et al. 2012.

Temporal Deductive Inferences

There is an equivalent type of inference in the temporal domain as to that involving spatial integration. According to the temporal coding hypothesis (Arcediano et al. 2003; Savastano and Miller 1998), the subject forms temporal maps between events experienced such as during a Pavlovian or instrumental conditioning procedure. Moreover, separately acquired temporal maps can be superimposed when they contain common elements, thereby forming an integrated map. This integrated map can be used to compute temporal relationships between events that had never been physically paired. Temporal integration has been shown using a variety of Pavlovian tasks such as second-order conditioning and sensory preconditioning (Barnet et al. 1997; Leising et al. 2007). In second-order conditioning, the CS1-US association is learned prior to the CS2-CS1 association. In sensory preconditioning, the CS2-CS1 association is learned prior to the CS1-US association.

Causal Deductive Inferences

Similar to cognitive maps involving spatial and temporal information, causal information can be encoded as a cognitive map. Such causal-based cognitive maps are typically referred to as causal models (Griffiths and Tenenbaum 2009; Waldmann et al. 2006). Once formed, a causal model can be used to deduce cause-effect relationships that have not previously been observed or experienced. One special type of causal inference involves the distinction between observing versus intervening on an effect (Sloman and Lagnado 2005; Waldmann and Hagmayer 2005). For example, observing that the window outside is wet might lead to the diagnostic inference that it has recently rained, which would be a cause for alarm to someone who hung up the wash to dry outside. On the other hand, if the individual knew that they had just watered the garden and that therefore they had caused the window to get wet,

they would discount the plausibility of it having recently rained and would therefore not be worried about the state of their laundry. Some evidence that animals can similarly make different causal inferences when presented with an effect that they merely observe versus with an effect that resulted from their own intervention comes from experiments in rats (Blaisdell et al. 2006). Rats in a conditioning chamber first observed a light followed by a tone (Light→Tone). Next, they observe the same light followed by presentations of a food reward (Light→Food). If the rat forms a causal map between each pair of events, then they should form a causal model consisting of light as a common cause of both tone and food. Causal model theory would then make specific predictions about what inferences about food the rat should make when the rat hears the tone at test. If the rat merely observes the tone, then the rat should diagnostically reason that the light must have occurred, and therefore should make the predictive inference that food should also be present. In this case, the rat should look in the feeder for food. If, on the other hand, the tone only occurred whenever the rat pressed a new lever that was placed in the chamber for the first time in the test session, the rat should infer that it, and not the light, had caused the tone, and therefore should not diagnostically infer the presence of the light. Because the rat does not expect that the light had just occurred, then it also should not expect food, which is an effect of the light (and not the tone or the lever). In this case, the rat should not look in the feeder. This was indeed what has been found in a number of experiments (Blaisdell 2016; Blaisdell et al. 2006; Blaisdell and Waldmann 2012; Leising et al. 2008).

Inference by Exclusion

Another type of decision-making that can occur under conditions of ambiguity involves inference by exclusion. Oftentimes, an individual is faced with the prospect of making a choice when the correct option that was available in the past is not immediately apparent. In these situations, evidence of absence can signal the likely correct choice. This is called *inference by exclusion*. A simple example of an inference by exclusion

is the popular childhood game of asking “In which hand am I holding it?”, where “it” is some small item – such as a coin – that can be enclosed in the hand without revealing its presence. If the decider chooses a hand and the questioner opens their hand to reveal an empty palm, the decider infers that the item must, by logical exclusion, be in the other hand.

Variations on this child’s game have been used as a procedure to study inference by exclusion in animals. At its most advanced level, it is of interest because human children likely learn the meaning of many words by way of an inference by exclusion – a form of word learning termed *fast mapping*. Inference by exclusion has been found in a variety of nonhuman animals, including dolphins (Herman et al. 1984), dogs (Kaminski et al. 2004), and rats (Blaisdell 2016), though the evidence for pigeons has been mixed (Aust et al. 2008; Lauffer et al. 2017).

Inference in Ambiguous Situations

Because they typically involve drawing an inference beyond prior direct experience or the information previously given, rational inferences are useful when information about a relevant aspect of the world is obscured from perception. Such situations create ambiguity about which of many possible states of the world is currently present. If a decision to respond or not respond depends on knowing about which of the two (or more) states the world is currently in, the individual may have to make an inference about the true state of the world. Recent experiments that investigate how rats deal with ambiguous states of the world during decision-making utilize a technique by which possible world states are first learned, and then at test, information about a cue necessary to discriminate between states is withheld (Blaisdell et al. 2009). For example, a rat may first be trained to make an instrumental discrimination based on a set of visual discriminative stimuli. After learning the visual discrimination, one of the visual cues, such as a light, can be covered by an opaque metal shield. Thus, the state of the light is ambiguous; it may be on or it may be off. There is no way for the rat to be certain. The rat might act as if it reasons that the light could be on, despite not being able to

see it. If this is the case, the rat might base its response by entertaining the possibility that the light, though covered, is actually on. Variations of this procedure have provided evidence that rats indeed are able to make hypothetical inferences about which are the likely states of the world under ambiguous conditions (Fast and Blaisdell 2011; Fast et al. 2016a; Waldmann et al. 2012), and this ability seems to be dependent on a functioning hippocampus (Fast et al. 2016b).

Induction

An inductive inference involves inducing a general rule, principle, or property by extrapolation from prior examples and evidence. For example, if you’ve seen hundreds of swans during your lifetime, and all of them were white, you might draw the inductive inference that all swans are white (cf. *deductive* inference in section [Logical or Deductive Inference](#)). Inductive inferences are generally more difficult to make given the uncertainty in (a) the accumulated evidence, and (b) the scope of the inference. For example, how many white swans must one observe before one can be certain to draw the inductive inference that all swans are white? And how broadly can you generalize this inductive inference, to all swans in England, all swans in Europe, all swans in the world, all water fowl closely related to swans, etc.? Furthermore, it only takes one counterexample (e.g., a black swan) to completely undermine the inductive inference. Even for humans, such black swan events can show the fragility of relying too heavily on inductive reasoning (Taleb 1997, 2012).

Causal Power

The topic of deductive causal inference has been discussed. Such deductions may require the acquisition of causal representations. Cause-Effect relationships cannot be directly observed, nevertheless, they may be induced through observation of the statistical and temporal relationships between events (Young 1995). Models that account for causal induction include causal model theory (Waldmann et al. 2006), models of causal power (Cheng 1997), and causal Bayes nets (Gopnik et al. 2004; Griffiths and

Tenenbaum 2009). Indirect evidence for causal induction in animals comes from the same rat experiments that were used to study deductive inferences from causal maps (Blaisdell et al. 2006). When a rat makes different deductive inferences about the likely presence or absence of food based on whether it had intervened to cause a tone or the tone was merely observed in the absence of an intervention, this implies that the rat had represented the light-tone and light-food relationships as causal, and not merely associative. That is, the rat must have formed a causal model linking light as a common cause of both tone and food. If these relationships were merely associative, then the rat should have expected food every time it heard the tone at test, regardless of whether the tone was merely observed or the result of the rat's intervention (see Leising et al. 2008, for further analysis of the special role of causal agency in deductive causal inferences).

A more direct test for causal induction in the rat comes from a study by Polack et al. (2013). Rats first learned to press a lever for water reinforcement. They then learned that lever pressing produced a tone. Following this, some rats learned that the tone is followed by a footshock (importantly, the levers were not present in the chamber during this training). At test, the thirsty rats were placed in the chamber with free access to the lever (that had previously earned water when pressed). Rats for which the tone had previously been followed by shock made significantly fewer lever presses than did rats for which the tone had not been paired with shock. If the pairings between tone and shock had established merely a tone-shock association, then the rats should not avoid pressing the lever (for water) because, even though they might have learned that pressing the lever is associated with the tone, *the tone merely predicts but does not cause the shock*. If, on the other hand, the rat encodes the tone-shock relationship as causal, then the rat should avoid pressing the lever, which in the past had also led to the presentation of the tone because the tone itself is perceived as a cause of shock, which is to be avoided. This experiment provides perhaps the best direct evidence for causal induction of a cause-effect representation in a nonhuman animal.

Concept Learning

The ability to discriminate stimuli based on category membership exemplifies conceptual behavior. Concept learning involves the process of stimulus classification based on a generalizable rule or property. There are three types of concept that animals have been shown capable of learning: perceptual, functional/equivalence, and abstract/relational. Category membership in a perceptual concept is defined by perceptual features of the item, as illustrated by the classic experiments by Herrnstein et al. (1976). Pigeons were reinforced with food for responding to photographs that contained pictures of people or parts of a person (e.g., a face) but were not reinforced for responding to photographs that did not contain pictures of people. Pigeons were able to learn this person/no-person discrimination. Pigeons were not merely learning the correct responses to each picture of the training set. Instead, they showed true concept learning in that their discrimination performance transferred quite accurately to novel pictures that did or did not contain humans in them. Much evidence has accumulated as to the general ability of nonhumans to acquire perceptual concepts (Lea et al. 1993; Wasserman et al. 1988) and include not only discrimination of objects but also of actions and movement (Cook et al. 2001; Dittrich et al. 1998).

A functional concept involves the classification of items based on their functional similarity, such as furniture, tools, etc. While the individual members of the category might be perceptually different from each other – such as a saw, sledgehammer, and miniature screw driver – they all share the same functional property, such as all being tools. Like a functional concept, an equivalence class is also defined by perceptually disparate items being grouped together based on sharing a common relation, such as an association with an outcome. By sharing a common associate, the items within the equivalence class become functionally equivalent. There is quite a bit of evidence that animals are capable of forming equivalence classes (see section [Stimulus Equivalence](#)). For example, after learning A–B and C–B associations (where A and C are sample stimuli presented on a center response key and B is a

comparison stimulus presented on a side response key), pigeons that then learn a new A–D association will automatically have an increased probability of choosing D following C, despite never having been explicitly trained on a C–D relation (Urciuoli and Lionello-Denolf 2001). Equivalence category learning has received extensive attention in the animal learning and cognition literature (Bovet and Vauclair 1998; Hall 1996; Honey and Hall 1989; Zentall 1998).

Perhaps the most abstract form of concept learning involves categorizing stimuli based on their relational properties. Most of this work involves training subjects on a Same/Different discrimination, by which responding to a set of items is reinforced if the items are all the same as each other (“Same” category) or not (“Different” category). After successfully learning the discrimination, Same-Different concept learning is demonstrated by above chance transfer to novel items that also belong to Same and Different categories (Blaisdell and Cook 2005b; Wasserman et al. 1995; Wright et al. 1984). Chimpanzees (Gillan et al. 1981; Oden et al. 1988), and perhaps baboons (Fagot et al. 2001), macaques (Flemming et al. 2011), and pigeons (Cook and Wasserman 2007), may also have the capacity for encoding higher-order relations (e.g., relational match to sample), such as those that underlie analogical mapping.

Rule Learning

Another form of inductive learning involves the abstraction of a rule that defines the underlying structure or regularity among a set or sets of stimuli. Rule learning is typically studied by presenting the structured input to the subject and rewarding the subject for choice responses that conform to the rule. Evidence for rule learning must come from tests involving novel stimuli to see whether the subject has abstracted the rule. The subject should be able to apply the abstracted rule to novel stimuli. If not, then the subject may have simply memorized correct responses from the training set of stimuli.

One of the simplest rules, and with the longest history of study in animal cognition, involves the matching-to-sample (MTS) and non-matching-to-

sample (NMTS) procedures. In these procedures, the subject is first presented with a sample stimulus (e.g., showing a red key light to a pigeon). Next two comparison stimuli are presented, one that matches and one that does not match the sample (e.g., a second red key light and a green key light). In a MTS procedure, the subject receives a reward (e.g., food) for choosing the comparison that matches the sample (red in this example); while in a NMTS procedure, the subject is rewarded for choosing the non-matching comparison (green in this example). While early work failed to find evidence for transfer to novel stimuli, therefore showing that such a procedure did not lead to true rule learning (Cumming and Berryman 1965), it has been subsequently shown that increases in the training set size led to increases in accuracy of transfer performance (Bodily et al. 2008), providing evidence for learning and applying an abstract rule of “choose same.”

More complex and sophisticated rule learning involves sequence information (Fountain 2008; Murphy et al. 2008), spatial patterns (Brown et al. 2000), number (Brannon and Terrace 2000; Scarf et al. 2011), syntax (Kako 1999), and artificial grammar (Herbranson and Shimp 2008; van Heijningen et al. 2013). Dissociations between bottom-up associative accounts and top-down rule induction accounts of serial pattern learning have been reported in rats (Wallace and Fountain 2002) and pigeons (Garlick et al. 2017).

Tool Use, Physical Cognition, and Theory of Mind

There are numerous reports of tool use in the animal kingdom. While many such instances likely involve noncognitive processes such as innate mechanisms (e.g., bird nests, spider webs, etc.), some examples have attracted the attention of more cognitive accounts. Some of the most likely candidates for rational processes in tool use involve apes and birds, and utilize physical traps (Mulcahy and Call 2006; Logan et al. 2014; Tebbich et al. 2007), string pulling (Taylor et al. 2010; Werdenich and Uber 2006), and even optimal tool construction or modification (Weir and Kacelnik 2006).

Some of the abilities that underlie rational tool use and construction involve more general processes that are collectively referred to as *physical cognition*. Physical cognition includes object permanence (Mendes and Huber 2004), causal effects of physical properties of objects (Call 2007; Helme et al. 2006), and means-ends relations (Krasheninnikova et al. 2013). A related domain of rational behavior involves predicting the behavior of, and communicating with, other agents. This domain is referred to as theory of mind and involves holding beliefs about one's own or other's beliefs and knowledge. Evidence for true theory of mind (i.e., mindreading) versus a theory of behavior (i.e., behavior reading) in non-humans is contentious (Call and Tomasello 2008; Heyes 2015).

Conclusions

I have reviewed evidence for rational processes in animals. Many animals show evidence for rational processes falling into two domains: deductive inference and inductive inference. These types of rational processes have been the direct focus of empirical study. Furthermore, there is a large and growing literature on physical cognition and theory of mind in animals, which touch on both domains of inference.

Given the extensive evidence for a variety of rational processes in animals, the question should be asked, are there any rational processes that seem beyond the capacities of nonhuman animals? Actually, there are. Abductive reasoning has yet to receive serious attention in the animal literature. An abductive inference involves the process of seeking and assessing explanations (Johnson et al. 2015; Turrisi 1997). Unlike deductive reasoning, in abductive reasoning the premises do not guarantee the conclusion. Instead, an abductive inference is derived from the strength of the premises and can be thought of as a likely (or best) explanation for the state of the world that brought about the conclusion. The few studies that have investigated whether nonhumans seek explanations have compared human children to chimpanzees. In contrast to human children, who have the natural proclivity to seek explanations for anomalous or unexpected events,

chimpanzees fail to display this capacity (Povinelli and Dunphy-lellii 2001).

Another rational process for which there is extensive evidence of absence in animals is true language. As opposed to many forms of communication found throughout the animal kingdom, true language is recursive and open-ended such that any meaning may (in theory) be communicated symbolically (e.g., through spoken or written word, signs, tokens, etc.). Even great apes, parrots, and dolphins that have received extensive symbolic training – such as with lexigrams, signs, or vocalizations – acquire only rudimentary properties of language, including syntax and vocabulary (Kako 1999; Pepperberg 2017). Some have taken this, and the poor quality of evidence for true theory of mind, to argue that there exists a deep divide between human and nonhuman minds (Penn and Povinelli 2007; Penn et al. 2008). This may be the case, but for now it is still an open, empirical issue that awaits further testing.

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