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Are There Minding Machines?

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Are there minding machines? In this paper, I consult historical, philosophical, and empirical sources in trying to answer this intriguing question. My historical and philosophical discussions focus on five famous Frenchmen (Michele de Montaigne, René Descartes, Salomon de Caus, Julien Offray de La Mettrie, and Jacques Vaucanson) and one famous American (William James). My review of empirical research focuses on five topics in contemporary comparative cognition: associative/causal learning, short-term memory, number discrimination, relational cognition, and metacognition. I conclude that *natural* minding machines do exist; they are humans and animals. Minding may be said to mediate the complex changes in behavior that humans and animals overtly exhibit. In that same sense, computers and other mechanical devices are often considered to be *artificial* minding machines. Nevertheless, many thinkers deem such artificial minding machines to be pale replicas of natural minding machines that are built from the "wrong stuff." No matter how much progress in artificial intelligence advances the computing power of these devices, they may never attain the intricacy and flexibility of nature's minding machines.

The *New York Times* of November 11, 2003 listed the 25 most provocative questions facing science. Three of them are of particular importance to comparative psychological science. *Number 4:* How does the brain work? *Number 14:* Can robots become conscious? And, *Number 16:* Are animals smarter than we think?

In the present paper, I will explore these three key questions while considering one overarching query: Are there minding machines? In attempting to answer this question from a natural scientific perspective, I will broadly interpret the terms "minding" and "machine" in my discussion of minding in humans, animals, and computers (for more on possible excesses of mentalistic interpretation, see Wasserman & Zentall, 2012).

I fully appreciate the daunting subject of this paper. So, I will consult historical, philosophical, and empirical materials in trying to shed light on the nature of "minding machines." My historical and philosophical discussions will focus on five famous Frenchmen (Michele de Montaigne, René Descartes, Salomon de Caus, Julien Offray de La Mettrie, and Jacques Vaucanson) and one famous American (William James). My review of empirical research will focus on five especially interesting topics in contemporary comparative cognition: associative/causal learning, short-term memory, number discrimination, relational cognition, and metacognition. Following these reviews and discussions, I will offer a few personal observations and analyses.

Historical and Philosophical Discussion

Before considering any experimental evidence, it will be helpful to provide some perspectives in the history of behavioral science and the philosophy of mind. So, let me now move to those notable individuals whose work will frame and inform our later discussion.

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Montaigne

Michele de Montaigne (1533-1592) was a Renaissance essayist. Although originally schooled as a lawyer, the character of Montaigne's writings has led to his being known as a philosopher or a "skeptical thinker." The work that is most pertinent to us here is his famous *Apologie de Raymond Sebond* (1580/2003), in which he critically considered the relationship between humans and animals.

Of humans, Montaigne wrote that presumption is our natural and original infirmity. Of all of earth's many creatures, we are the most miserable and frail; yet, we are also the most arrogant. That arrogance leads us to ascribe divine attributes to ourselves and to separate ourselves from all other creatures.

Montaigne raised penetrating questions about this arrogant placement of humans apart from and above animals. Is it really so easy to say with certainty what decisively distinguishes humans from animals? And, by what comparison between them and us do we ascribe brutishness only to them? Montaigne believed that skeptical inquiry into animal behavior can answer these two profound questions (Silver, 2002).

Montaigne's own skeptical inquiry into animal behavior dealt mainly with what he found in ancient texts. These works suggested to him that animals communicate socially, exhibit many different forms of craftsmanship, and display some signs of logical decision making (one well-known example being Chrysippus's dog; see Rescorla, 2009, for further discussion of this story and see Lauffer, Castro, & Wasserman, 2017, for a recent study of pigeons' possible reasoning by exclusion). Those behavioral signs were the only clues that were then available for skeptical inquirers to assess the cognitive processes of animals (Melehy, 2005).

In evaluating the dichotomy between animals *versus* humans, Montaigne adopted the following rule: *From like results we must infer like faculties.* This rule prompted Montaigne to conclude that human communication and reasoning cannot be firmly distinguished from animals' perhaps less advanced abilities (Gunderson, 1964). Thus, humans and animals must obey the same laws of nature, leading to the humbling position that there is no special place for humans among all of nature's creatures (Melehy, 2005; Silver, 2002). Montaigne's views certainly accord with those espoused by many of today's environmentally focused authors.

Descartes and Caus

René Descartes (1596-1650) offered a dramatically different view of humans and animals. Of course, Descartes was the most celebrated French philosopher. He was also a mathematician and an anatomist. And, he famously espoused the philosophical doctrine of mind-body dualism.

In order to appreciate Descartes' position on mind and body properly, we have to expand our consideration to humans, animals, and machines. We must do so because machines played a particularly prominent part in shaping Descartes' views.

As did many of his learned contemporaries, Descartes visited a number of celebrated gardens in Europe. One of these was located in Saint-Germain-en-Laye, only 12 miles from Paris. There, amazing automatons (self-operating machines) were featured. Many of those marvelous devices were fabricated by Salomon de Caus, whose lifelike automata were arrayed artistically, "representing everything from birds, fish and beasts to peasants or princes amid mythic scenes" (Werrett, 2001, p. 134).

Caus (1576-1626) was an engineer, who designed hydraulic automata for the scenic grottoes in Saint-Germain-en-Laye and in several other European venues. Those hydraulic automata were the source of considerable fame and fortune for designers like Caus. These designers carefully concealed the designs of their machines, for to have revealed those secrets would have deprived the spectators of their sense of wonder and denied the designers their lucrative livelihoods.

Descartes was fascinated especially by these hydraulic machines. But, beyond this fascination, Descartes saw real scientific possibilities for understanding the design and operation of these machines. So, he set to work to discover the secret workings of these *human made* creations; and, he later deployed the same investigative methods to discover the secret workings of *nature's* creations.

Focusing on the operating properties of machines in his *Discours de la méthode: Météores* (1637/Adam & Tannery, 1908), Descartes focused his talents and energies on the rainbow fountain. This device was a notable wonder of the Renaissance garden, in which a fine mist of water was sprayed skyward to catch the sunlight and to produce a rainbow on demand. This machine was to serve as a test case for Descartes' scientific method, which he utilized in order to understand the workings of the rainbow fountain through experiment and mathematics (Werrett, 2001).

That test proved to be highly successful. Indeed, it was so successful that divulging the workings of this *artificial* device actually led to Descartes' explaining *natural* rainbows, thereby reinforcing his conviction that *all* rainbows—whether natural or artificial—were produced by the same mechanical principles involving the reflection and refraction of light. Descartes thus concluded that all of nature may be a glorious machine: one vastly more complex and on a far grander scale than any human contrivance.

Descartes discussed the nature of human beings in his famous *Trait*é *de l'homme* (1632/1972). There, he proposed that we too are machines. But, humans are vastly more intricate than hydraulic automata. Unlike machines, humans are capable of thought and language. Critically, we have an immaterial "rational soul," existing beyond the body and only influencing bodily movement via the pineal gland. "Once the having of a soul has been divorced from the living body, the way is clear to thinking of the body as a machine" (Avramides, 1996, p. 33).

Descartes proceeded to discuss the nature of animals in his famed *Letter to the Marquess of Newcastle* (1646/Ariew, 2000). In it, Descartes argued that animals are nothing more than beastly mechanisms—*bête-machines* (Gunderson, 1964; Newman, 2001). Animals do have sensations and passions; but, these are merely organic reactions. Animals lack thought and language. Animals lack abstraction, mathematics, and metacognition (Smith, 2005). And, animals have neither mind nor "rational soul," thus preventing animals from engaging in any complex cognitive processes (Avramides, 1996).

Contrasting animals *versus* machines, Descartes contended that animals are mindless bodies like machines. So, he put animals into the category of automata and insisted that they behave mechanically—just like clocks (Erion, 2001). Contrasting animals *versus* humans, Descartes conceded that animals and human bodies are both organic machines. But, he argued that our souls make humans special (Erion, 2001); we also have language and reason, whereas animals do not. Reason—what Descartes memorably called the *universal instrument* (Wilson, 1995)—allows humans to respond adaptive and flexibly to any and all conditions as well as to attain mastery over nature (Melehy, 2005).

La Mettrie and Vaucanson

Julien Offray de La Mettrie (1709-1751) was both a physician and a philosopher. His staunch materialist ideas were at odds with the prevailing religious notions that were foundational to Descartes' dualism. La Mettrie too had interesting and important things to say about humans, animals, and machines.

La Mettrie agreed with Descartes that animals were machines. He also agreed with Descartes that animals had no souls. But, La Mettrie pursued Descartes' idea of the *bête-machine* to its logical end: *l'homme machine* (1747/1996). Daringly, La Mettrie believed that humans too are machines that lacked souls: "Like Descartes, La Mettrie thought that [the] body operates in accord with mechanical laws. Unlike Descartes, however, he denied the existence of any soul whose essence is entirely distinct from extended matter…. The superiority of humans over animals he deemed variously a function of their more developed brain structure, bodily organization or needs" (Rosenfield, 1941, pp. 143-144).

What did La Mettrie deem to be the relationships among humans, animals, and machines? Humans do not essentially differ from animals. Unlike human made machines, humans and animals are highly complex biological machines, whose matter and organization produce life, feelings, intelligence, and consciousness (Gunderson, 1964; Vartanian, 1993). La Mettrie believed that nature created these biological machines with even more elaborate art than Jacques Vaucanson crafted his automatons.

Jacques Vaucanson? Yes, another engineer was to have a significant influence on biological and psychological science!

Vaucanson (1709-1783) was an extraordinarily talented engineer who turned the mechanistic ideas of La Mettrie and Descartes into technical reality (Wood, 2002). Vaucanson endeavored to create what he called a moving anatomy—*anatomie mouvante.* The automata that he constructed have been considered to represent philosophical experiments (Riskin, 2003b), which sought to answer two intriguing questions. Which aspects of real creatures can be reproduced in machinery? What do such automata reveal about real creatures?

Vaucanson's most celebrated creation was a mechanical duck, which became the most talked-about bird in all of Europe (Figure 1). Vaucanson became quite rich as a result of exhibiting the duck and his other automata. Indeed, Vaucanson was even elected to *L'Academie des Sciences* as an "Associated Mechanician," a position that was created solely to honor him.

Figure 1. **Medallion commemorating Jacques Vaucanson—and his famous Digesting Duck**. (Top) Front view. (Bottom) Reverse view.

What was so special about Vaucanson's mechanical duck? It had a weight-powered mechanism of over 1,000 movable parts that was hidden inside the bird and inside the pedestal on which it stood. Each wing had over 400 articulated pieces. And, the duck's many and varied actions included drinking, dabbling, gurgling, rising, crouching, stretching and bending its neck, plus moving its wings, tail, and feathers. All of these intricate anatine actions were fine and dandy. But, the duck's greatest claims to fame were that it consumed grain and, after a suitable interval, it defecated. Good show!

Vaucanson's famous avian automaton is sometimes called The Digesting Duck. But, this moniker turns out to be a flagrant misnomer. The duck did not digest food at all—it was a fraud! The ingested food actually progressed no farther than the base of the duck's neck. Fake excrement—that had earlier been loaded into a hidden repository near the duck's tail—was expelled after a programmed postprandial delay. The debunker of the Digesting Duck was none other than Jean Eugène Robert-Houdin, another famous French mechanician and magician (Riskin, 2003a).

Today, instead of mechanical ducks imitating real ones, computerized creatures like Aibo—the dog-like robot recently reintroduced by the Sony Corporation—are becoming increasingly lifelike. We may not be fooled by this charade, but real dogs may have been tricked when they were allowed to interact with Aibo (Kubinyi et al., 2004).

Riskin (2003b) intriguingly suggests that Vaucanson's Duck has commanded so much attention for so long because it dramatizes two contradictory claims: (a) Animals are merely machines. (b) Animal life is irreducible to mere mechanism. Because this tension persists to this day, Riskin proposes that we still live in the age of Vaucanson. We are continuing a project that began 250 years ago by the Digesting Duck—that didn't. Riskin (2016) has further expanded on the many philosophical and scientific issues raised concerning lifelike and living machines.

Beyond these philosophical issues, Vaucanson's Duck poses a very practical problem for comparative psychology: How can we effectively distinguish *profound* from *superficial* resemblance? After all, seeing is not always believing. Large silvery predators swim in the depths of the sea; but, sharks are fish and dolphins are mammals. Bats, budgerigars, and bees all fly; but, these airborne animals are mammals, avians, and insects, respectively.

In point of fact, there is no sure and simple way to discriminate profound from superficial resemblance. Yet, a hint from the writings of none other than William James suggests how we might be able to do so.

James

Over a century ago, America's first great psychologist, William James (1842-1910), complained that "...it is the bane of psychology to suppose that where the results are similar, processes must be the same" (1890, p. 528). James clearly took exception to capitulating to Montaigne's earlier adage that: *From like results we must infer like faculties.*

James underscored the severity of this interpretive problem by posing a telling hypothetical misstep: "Psychologists are too apt to reason as geometers would, if the latter were to say that the diameter of a circle is the same thing as its semi-circumference, because, forsooth, they terminate in the same two points" (1890, p. 528). This geometrical example suggests a promising, practical solution to the problem of deciding whether the same process underlies similar behaviors in different organisms—a prime challenge of comparative psychology.

Suppose that we systematically vary some independent variable across *many*—not just *two*—different parametric values and we observe the effects of those variations on the behavior of different species of animals. Now, suppose that those parametric functions closely parallel one another. Most researchers would agree that such striking "parametric parallels" would be extremely unlikely to have arisen by chance; instead, those parallels suggest a common process at work in the different species. Thus, *parametric study* is not just workmanlike psychological science; it is an invaluable tactic to deploy in comparative behavioral study (see Wright, 2013 for a compelling review of such "functional analyses" of human and animal cognition).

Empirical Research in Comparative Cognition

We now turn to five domains of contemporary psychological science in which clear parametric parallels have been documented in humans and animals, thereby suggesting the operation of common processes in associative/causal learning, short-term memory, number discrimination, relational cognition, and metacognition. I selected these particular realms because they are basic to adaptive behavior and because they remain active and productive areas of investigation in comparative cognition. Many more areas would surely have merited discussion (see Zentall & Wasserman, 2012 for a rich compendium of such areas of study).

Associative/Causal Learning

Causation is fundamental to natural science. Many researchers have come to believe that identifying and verifying the interrelations between natural phenomena requires advanced logical or statistical inference. If that were so, then these processes might very well be uniquely human. None other than David Hume (1711-1776) vigorously disagreed with this point of view.

For Hume, a purely *mechanical* associative process leads to the impression of causation. Furthermore, for Hume, the same process operates in humans and animals. Why did Hume arrive at these two striking conclusions? Because, he said, survival cannot depend on the *deliberateness* and *fallibility* of logic and reason.

According to Hume, causal beliefs actually arise from the association of ideas. Because they develop from the repeated conjunction of events, associations must rise to their point of perfection by degrees. *Thus, causal judgments should emerge progressively, as do associative learning curves.* Empirical evidence shows that they do (Wasserman, Kao, Van Hamme, Katagiri, & Young, 1996).

Furthermore, causal beliefs cannot produce assurance in any *single* event as the cause unless it is paired frequently with the effect and unless it is superior to *rival* causes. *Therefore, as in the case of associative cue competition, discounting of inferior rivals should occur in causal judgment.* Is that also the case?

Several prominent cue competition effects have been shown to occur in associative learning: the two most familiar are *blocking* and *overshadowing* (Wasserman & Miller, 1997). Another famous case of cue competition is the *cue validity* effect first reported by Wagner, Logan, Haberlandt, and Price (1968). Key to the cue validity effect is that Cue X, the target cue, is paired *equally* often with the outcome in all of the arranged conditions. However, Cues A and B are paired *differently* with the outcome in the various conditions.

Wasserman (1974) showed how control by Cues A, B, and X systematically changes as a function of the disparity in the probability of the outcome after Cues A and B. He gave pigeons 2-key compound stimuli and separately measured pecking at each element. The AX and BX trials occurred equally often. The correlation of Cues A and B with food *varied* across five different experimental conditions; but, Cue X was paired *equally* with food in all five of the conditions.

Responding to Cue A rose as it was increasingly paired with food, whereas responding to Cue B fell as it was decreasingly paired with food. Beyond these obvious effects, responding to Cue X fell as Cues A and B came to signal differentially the presentation and nonpresentation of food. In other words, despite Cue X having been paired with food 50% of the time in all of the conditions, the relative validity of Cues A and B dramatically affected responding to Cue X. The more valid were Cues A and B, the less valid was Cue X and the less responding it prompted.

Was this cue validity effect limited to rats, rabbits, and pigeons in operant and respondent conditioning situations? To find out, the possibility of a cue validity effect in human causal judgment was studied analogously with an allergy diagnosis task developed by Wasserman (1990). College students had to rate the causal effectiveness of three possible allergens: shrimp, strawberries, and peanuts. The three allergens were given in two pairs: AX and BX, just as in the earlier conditioning experiments with animals. The association of these compounds with a hypothetical patient's allergic reaction was varied across five different experimental conditions, just as in the prior pigeon project of Wasserman (1974).

The results were the same. Causal ratings of Cue A rose as it was increasingly paired with the allergic reaction, whereas causal ratings of Cue B fell as it was decreasingly paired with the allergic reaction. And, causal ratings of Cue X fell as Cues A and B came to signal differentially the occurrence and nonoccurrence of the allergic reaction.

Thus, causation and association are strongly related empirically. Both exhibit acquisition. Both exhibit cue competition. And, both phenomena can be explained by elementary associative learning principles. Reason is *not* necessary to explain either phenomenon.

In Hume's words, "Any theory, by which we explain the operations of the understanding, or the origin and connection of the passions in man, will acquire additional authority, if we find, that the same theory is requisite to explain the same phenomena in all other animals (1777/1951, p. 104)." Such a theory does seem plausible; it is the Rescorla-Wagner (1972) theory, which instantiates Hume's associative principles with an elegant mathematical model.

Of course, the Rescorla-Wagner model is not the last word in associative learning theory (Le Pelley, Griffiths, & Beesley, 2017). The prime empirical challenge to that theory—the retrospective revaluation phenomenon termed *backward blocking*—has sparked considerable interest (Miller & Witnauer, 2016), with one account emerging from an expansion of the Rescorla-Wagner model (Wasserman & Castro, 2005).

Short-term Memory

Humans and animals alike can retain information for one-trial-only use over several seconds, thereby exhibiting short-term or working memory. Furthermore, when multiple items must be retained, memory for those items often follows a characteristic function: initial items (primacy) and terminal items (recency) are better remembered than are items in the middle of the list. This familiar U-shaped function represents the *serial-position effect*.

Wright, Santiago, Sands, Kendrick, and Cook (1985) parametrically explored this serial-position effect in four different species: humans, rhesus monkeys, capuchin monkeys, and pigeons. To all four species, Wright et al. showed lists of four visual stimuli—one after another—on the *upper* of two viewing screens. They showed a single probe item on the *lower* viewing screen after fourth list item had been removed. If the probe item had been in the list, then one button response produced reward; if the probe item had not been in the list, then a second button response produced reward. No reward was given following any other button responses.

All four species evidenced the serial-position effect. They did so at *intermediate* delays between the last list item and the two-button choice test. However, at *short* delays, all four species showed a continuously increasing memory function, with the last list item being the best remembered—recency. And, at *long* delays, all four species showed a continuously decreasing memory function, with the first list item being the best remembered—primacy. These parametric parallels are truly remarkable and they strongly suggest that common memory processes are mediating the choice behavior of all four species in this list memory task.

It is particularly worth noting that these patterns of behavior were exhibited by all four species despite disparities in the visual stimuli that they were shown and in the retention intervals that they were given. For example, the longest retention interval was 10 s for pigeons, it was 30 s for rhesus and capuchin monkeys, and it was 100 s for humans. So, quantitative differences in memory capacity may very well exist. Those quantitative differences, as well as the profound qualitative similarity of serial memory, all stand to be enlightened by ongoing and future behavioral and neurobiological investigations (Konecky, Smith, & Olson, 2017; Miyamoto, Osada, & Adachi, 2014).

Number Discrimination

Both humans and animals can discriminate the number of items they are shown at any given time, attesting to stimulus control by this abstract environmental property. How similar is the number discrimination process in different species?

Cantlon and Brannon (2006) assiduously investigated this question in humans and rhesus monkeys. On each trial, two visual arrays containing different numbers (from 2 to 30) of small squares were shown. The organism's task was to respond first to the array that contained fewer items. For monkeys, the report response was touching the smaller array, thereby activating a touch screen with a finger. For humans, the report response was bringing a cursor into contact with the smaller array by operating a computer mouse. The investigators measured both choice accuracy and reaction time.

The results for monkeys and humans were strikingly similar. As the smaller and the larger numbers of items were made more similar to one another—thereby increasing the difficulty of the numerical discrimination—accuracy fell and reaction time rose. These findings suggest that monkeys and humans each represent numbers as large as 30 as perceptual magnitudes and that they rely on a comparison process which closely accords with Weber's Law. Cantlon and Brannon (2006) propose that the close parametric similarity in the behavior of monkeys and humans provides the strongest evidence to date of a single nonverbal, evolutionarily primitive mechanism for representing and comparing numerical values (see Castro & Wasserman, 2016 for very similar results for pigeons).

This interesting work on numerical discrimination has expanded dramatically over the past decade to include both behavioral and neurological investigations (Nieder & Dehaene, 2009). The work has further suggested that a common magnitude system in the brain underlies the judgments of many different species of animals (Leibovich, Katzin, Harel, & Henik, 2017), including birds (Castro & Wasserman, 2016; De Corte, Navarro, & Wasserman, 2017), further elucidating the biological substrates involved in numerical and magnitude discrimination.

Relational Cognition

Comparative psychology is replete with confident proclamations of human exclusivity by philosophical luminaries. Especially famous and germane is that of John Locke, who in his 1690 work, *An Essay Concerning Human Understanding*, confidently opined: "I think, I may be positive … That the power of Abstracting is not at all in [Brutes]; and that the having of general Ideas is that which puts a perfect distinction betwixt Man and Brutes; and is an Excellency which the Faculties of Brutes do by no means attain to" (Locke, 1690/1975, p. 159).

Over the past several years, such philosophical proclamations have been tested empirically. We have now learned that several different animal species are indeed capable of acquiring and transferring a wide range of relational discrimination problems (recently reviewed by Wasserman, Castro, & Fagot, 2017).

One of the most intensely studied of these relational discrimination problems is same-different discrimination learning. Here, the behavioral evidence suggests that many species of nonhuman animals—from bees to chimpanzees—join humans in discriminating first-order same-different relations. Animals can reliably report whether two stimuli are identical (A = A or B = B) or nonidentical (A ≠ B). Animals can also transfer that behavior to untrained experimental stimuli (see additional reviews by Wasserman & Young, 2010 and Wright & Katz, 2006).

An even more advanced form of same-different discrimination involves second-order relations between first-order relations. Appreciating such higher-order relations may be foundational to analogical reasoning. Can only human beings discriminate such higher-order relations? Some authors have suggested that one way to find out is by giving subjects a task that captures the gist of analogy: namely, relational matching-to-sample (Thompson & Oden, 2000). This task arranges the relevant logical arguments with visual stimuli, and it can readily be given to nonhuman animals as well as human beings.

Once again using letters of the alphabet for explanatory purposes, picking test pair BB would be correct if the sample pair were AA, whereas picking test pair EF would be correct if the sample pair were CD. Stated logically, A:A as B:B (same = same) and C:D as E:F (different = different). It is important to note that no items in the correct test pair physically match any of the items in the sample pair; due to this critical constraint, only the analogical relation of sameness can be used to solve the task.

Early research suggested that only humans and apes can learn this task (reviewed by Penn, Holyoak, & Povinelli, 2008); however, a more recent project has found that crows too can solve the relational matching-to-sample task. Smirnova, Zorina, Obozova, and Wasserman (2015) first trained hooded crows on several different tasks in which they had to match *individual* items that were the same as one another. The crows were presented with a tray containing three cups. The middle cup was covered by a card picturing a color, a shape, or a number of items. The two side cups were also covered by cards: one the same as and one different from the middle card. The cup under the matching card contained food, but the cup under the nonmatching card was empty. Crows rapidly learned to choose the matching card and did so more quickly as they transitioned from one task to the next.

Then, the critical test was given. Each card now pictured a *pair* of items. The middle card would display pairs AA or CD, and the two side cards would display pairs BB and EF. The relation between one pair of items must be appreciated and then applied to a new pair of items to generate the correct answer: the BB card in the case of AA or the EF card in the case of CD.

Not only did the crows correctly perform this task, but they did so spontaneously, from the very first presentations, without ever being explicitly trained to do so! It seems that initial training to match identical items may have enabled the crows to grasp a broadly applicable concept of sameness, which they could apply to the novel two-item analogy task. Such robust and uninstructed relational matching-to-sample behavior arguably represents the most convincing evidence yet of analogical reasoning in a non-primate animal (see Obozova, Smirnova, Zorina, & Wasserman, 2015, for highly similar results with parrots).

We do not yet know if and how the crows' prior training on an individual-item matching-to-sample task enabled them to solve the relational matching-to-sample task. However, it seems likely that, without such prior training on which successful relational matching-to-sample could build, success would have been much less likely or even impossible. Carefully studying this matter may not only elucidate possible species differences in relational reasoning, but also its development in human and nonhuman animals. This line of work seems essential to explicate the nature of relational cognition. The corresponding pursuit—examining the verbal and nonverbal antecedents to human relational cognition—is equally vital within the realm of developmental psychology (see Ferry, Hespos, & Gentner, 2015 for encouraging results with infants).

And, what of parametric parallels between human and animal behavior? Here, Fagot, Wasserman, and Young (2001) compared relational matching-to-sample in humans and guinea baboons using, not only *pairs* of items, but *arrays* of as many as 16 items. Now, samples could vary from all same to all different through various mixtures of same and different items. Members of both species showed systematic rises in choosing the all-different choice alternative as the sample arrays progressively displayed all-same, through some-different, to all-different items. That rise proved to be steeper for humans than for baboons—a quantitative rather than a qualitative difference—thus requiring further research for explication.

Metacognition

Since Descartes, philosophers have held that knowing one's own mind is central to consciousness. But, is metacognition uniquely human? Do animals also know if and what they know? And, how can you tell if they do?

Several groups of researchers have studied metacognition in such diverse animals as rats, pigeons, monkeys, and dolphins (see Carruthers, 2008 for a review and critique). The earliest work with monkeys and humans was conducted by Shields, Smith, and Washburn (1997).

Monkey and human subjects were shown a visual display involving different densities of dots. If the display involved sparse dots, then subjects were to make one arbitrary report response to receive reward. If the display involved dense dots, then subjects were to make a second arbitrary report response to receive reward. The novel twist to the experiment was that if subjects were unsure as to which of the two responses to make, then they could make a third "uncertain" response, which provided a smaller, but more likely reward.

The pattern of results across a wide range of dot densities was very similar for monkeys and humans. As dot density rose, the probability of "sparse" reports fell and the probability of "dense" reports rose. Where the two functions crossed, subjects were most likely to make the "uncertain" response, with the probability of such responses declining to either side of that point.

Considerable controversy continues to surround these and other related findings, particularly whether they uniquely support a metacognitive interpretation as opposed to other rival accounts (Carruthers, 2008; Le Pelley, 2012, Smith, Couchman, & Beran, 2012; Smith, Zakrzewski, & Church, 2016). Nevertheless, one cannot help but be impressed by the close parametric parallels that hold here for monkey and human discrimination behavior.

Overview

My selective review of empirical research in comparative cognition discloses that clear parametric parallels exist between human and animal behavior. These parallels hold in such diverse realms as associative/causal learning, short-term memory, number discrimination, relational cognition, and metacognition. These strong *parametric parallels* argue against superficial similarity and in favor of profound resemblance in the cognitive processes of humans and animals. Pursuit of further parallels surely seems warranted.

Observations and Analyses

To organize my final observations and analyses, it will be useful to return to the three original questions from the 2003 *New York Times* that opened this paper.

How Does the Brain Work?

Very well, indeed! Brains remember past, they act in present, and they prepare for the future. These and other cognitive functions enable organisms to adapt to the complex and ever-changing contingencies of survival to which they are ceaselessly exposed. Elucidating the biological mechanisms of cognition is the task of cognitive neuroscience.

Neuroscience has divulged that brains are not hydraulic devices, telephone switchboards, or digital computers. Reducing brains to human-made machines could have some heuristic merit; but, 250 years of such efforts may have been far less fruitful than have direct studies of human and animal behavior and biology.

Neuroscience has also revealed that brains are not designed intelligently. In his provocative book, *The Accidental Mind*, David Linden (2007) persuasively argues that the human brain is a cobbled-together mess: a weird merger of ad hoc solutions that have accrued over millions of years of evolution. The brain's quirky, inefficient, and sometimes bizarre organization nevertheless functions quite impressively given its haphazard provenance.

Linden concludes that the brain is not an optimized, general problem-solving machine. It is clearly not the biological organ of reason—Descartes' so-called "universal instrument." Our "accidental brain," Linden claims, accounts for the very nature of human nature.

Can Robots become Conscious?

From film, literature, and even academic circles, there is currently rampant speculation that computers and robots may inevitably become conscious (Kak, 2017). Interestingly, there turns out to be a surprisingly long history to the futuristic idea of machine consciousness (Reggia, 2013). Consider this passage written in 1872 by English author Samuel Butler (1920):

> There is no security … against the ultimate development of mechanical consciousness, in the fact of machines possessing little consciousness now. A mollusc has not much consciousness. Reflect upon the extraordinary advance which machines have made during the last few hundred years, and note how slowly the animal and vegetable kingdoms are advancing. The more highly organized machines are creatures not so much of yesterday, as of the last five minutes, so to speak, in comparison with past time. (p. 233-234)

These pregnant lines come from "The book of the machines" in Butler's anonymously published novel, *Erewhon*. They foretell of machines evolving their own brand of consciousness by analogy to the evolution of consciousness in humans and other animals.

The prospect of conscious robots or other artificial intelligence systems arises not only from science fiction, but from the philosophical notion of *functionalism*: the doctrine that what makes something a thought, a desire, or any other kind of mental state does not depend on its internal construction, but only on its function within the system of which it is a part (Braddon-Mitchell, 2002). This notion permits other organisms or even machines with very different physical constitutions to have mental states if they too exhibit sufficiently similar behaviors.

So, is it plausible to believe that computers can become conscious? I'm inclined to say "no." Nor can they digest food or fall in love. As simulacra, robots and computers are simply not made of the "right stuff." Matter matters!

I've been challenged in my belief that computers cannot become conscious. Critics have contended that, if only we could properly mimic the organization of the nervous system—with silicon chips, plastic bits, or rubber bands—then consciousness would emerge. I suspect that the very audacity of this claim makes it appealing to some. Yet, to me, it seems like a nonstarter.

But, do not take my resistance to computer consciousness as gospel. Consider as well the piercing comment of John Searle in a February 4, 2007 interview with the *Boston Globe*: "Defined by the manipulation of zeroes and ones, the computer model can tell us nothing about how our brains produce mind, consciousness, and a sense of self." Add to that Richard Feynman's tart assessment of a programmed computer or robot being nothing more than: "a glorified, high-class, very fast but stupid filing system."

Finally, consider what roboticist Rodney Brooks says about artificial intelligence and computer cognition and consciousness: "It is only an external observer that has anything to do with cognition, by way of attributing cognitive abilities to a system that works well in the world but has no place where cognition is done…. Cognition is only in the eye of the observer" (1999, pp. x-xi).

Perhaps folks are simply being overeager in attributing subjective experiences to entities that truly lack them, but merely behave in ways that conjure those notions based on our own private experiences. At least I'm in good company with others who question the plausibility of computer consciousness.

Are Animals Smarter than We Think?

Of course! We all appreciate how difficult it is to investigate animal cognition. Yet, as our experimental methods have improved, so too has our understanding of animal intelligence (Zentall & Wasserman, 2012).

We also appreciate that humans and animals represent highly related life forms, which exhibit many complex cognitive behaviors. Parametric parallels suggest that common biological mechanisms lie at the root of their cognition and behavior. However, like Vaucanson's Duck, computers and other mechanical devices are pale replicas built from the "wrong stuff."

Nevertheless, pursuing Descartes' agenda of objectively studying humans and animals *as if* they were machines does have definite heuristic merit. Robust laws of behavior and cognition are emerging from such study. For a natural science of mind, I see no reasonable investigative alternative.

So, yes, minding machines do exist; they are humans and animals. Minding mediates the complex changes in behavior that humans and animals exhibit. Minding's their business! Humans and animals are machines only insofar as their behaviors are the products of biological mechanisms. We might therefore call them "minding meat" or "meat machines" (Smith, 2005). As powerful as we may construct them, or they may eventually construct themselves, no artificial devices are likely to duplicate nature's own minding machines.

Epilogue

Let me close by considering some recent thoughts by the prominent British philosopher Andy Clark. In an interview in the April 2, 2018 *New Yorker*, Clark abandons what he had long deemed to be an essential premise of AI: namely, that machine functionalism is plausible. The *software* of minding might simply be unable to run on just any *hardware*. If cognition is truly a biological enterprise, then there are going to have to be very clear limits to artificial intelligence.

Why might that be the case? Clark envisions such limits because the biological bits that enable cognition are themselves organized *systems*, not insulated *components*. As living organisms, humans and other animals are built system upon system upon system. In his words:

> The smallest systems are the individual cells, which have an awful lot of their own little intelligence, if you like—they take care of themselves, they have their own things to do. Maybe there's a great flexibility in being built out of all these little bits of stuff that have their own capacities to protect and organize themselves. I've become more and more open to the idea that some of the fundamental features of life really *are* important to understanding how our mind is possible.

Clark's proposal can then be seen to resemble that of the famed German philosopher Gottfried Wilhelm Leibniz (1646-1716). If you equate the words *system* and *machine* in the following lines, then you can grasp Leibnitz's definition of an organism: a natural machine, "in which each part is a machine, whereas the parts of our artificial machines are not machines. No human-made machine could be a machine in all its parts. Natural machines, that is living bodies, remain machines in their least parts to infinity (quoted in Riskin, 2016, p 107)."

Such philosophical speculations notwithstanding, the challenge that lies ahead for behavioral and cognitive neuroscientists is to understand nature's minding machines armed solely with their own minds. That's the ultimate contest!

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