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Continuity of Cognition Across Species: Darwin in Cyberspace

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People have wondered for millennia whether other species experience and understand the world and their actions in it in the same manner as humans. As with every other aspect of understanding the world, various cultures have developed their own beliefs of the relations among humans and nonhuman animals, of animal behavior, and of animal intellect. Some cultures, such as many Native American tribes, attribute deep wisdom or supernatural powers to various animals. Current views of the mental lives of animals in North American science, and in Western science in general, reflect the particular cultural heritage of European enlightenment philosophy, from which empirical science as we know it has developed since the 1700s. The Enlightenment view of human uniqueness has been an uncomfortable bedfellow in the past century and a half with the Darwinian doctrine of phylogenetic continuity, including continuity of intellect and of experience. We are still wrestling with the disjoint notions of human uniqueness and phylogenetic continuity, a schism reflected everywhere in psychological science.

Comparative psychologists come down on the other side of this fence, regarding cognitive processes in nonhuman species as shared with humans in some way or ways. These processes are known or are to be discovered through diligent empirical inquiry of behavior, a position that has philosophical support from those more impressed with action and feeling than with introspection (e.g., Dewey, 1942; Johnson, 1987; Langer, 1967; Rorty, 1982). Comparative psychologists studying nonhuman primates have been at the forefront of this group (e.g., Robert Yerkes, Wolfgang Köhler, Harry Harlow, and David Premack), although psychologists studying other kinds of animals are also represented (e.g., Edward Tolman, Louis Herman, and Irene Pepperberg).

Through the study of behavior, comparative psychologists have adopted several empirical strategies to examine the mental prowess of various species and the prospect of mental continuity across the animal kingdom. Earliest efforts involved collection of anecdotes of apparently intelligent behavior in nonhuman species (Romanes, 1884), a method that is still occasionally adopted even in contemporary times (Whiten & Byrne, 1988). However, psychologists soon turned to experimental methods, using highly constrained (and therefore replicable) testing conditions, presenting simple problems to an individual animal that could be solved repetitively in multiple "trials" (e.g., Harlow, 1949; Thorndike, 1911). This experimental strategy still dominates contemporary comparative psychology. Often, the aim of the experiment is to identify how experience increases the probability of a particular form of solution (i.e., learning); this method can also be used to identify perceptual capabilities and preferences. Others have presented problems in a free-form context, in which the individual may demonstrate variable behaviors to achieve a goal (e.g., Köhler, 1925). This approach is more concerned with the production of flexible behavior than with the rapidity of learning a specific behavior. All of these strategies have value; we can expect that all will continue to be used.

Enter the computer in the mid-20th century; our science has changed dramatically because of this technological advance. Church (1983, 1993, 2001) highlighted the numerous ways that computers have affected our lives as researchers. At first computers changed our science in practical ways. Computers freed us from reliance on card-catalog searches and printed indices of literature and afforded new features in experimental design, such as automatization and randomization. The use of computers to run our experiments increased our control of the parameters of our tasks as well as eased the burdens of collecting, storing, and analyzing our data. After attaining our results, the computer provided us with an efficient means to present these data to the research community.

As important as these contributions are, we believe that they should be regarded as the "first generation" benefits. We are now in the "second generation" of applications of technology to our field, and we have opportunities to develop entirely new ways of examining behavior and new vistas for psychological experimentation. In this sense, just as genomics is leading biological science to new theories and new ways of studying living systems, advances in technology are leading psychological science to develop new research areas (i.e., cyberpsychology), new theories, and new paradigms of studying cognition and action (Loomis, Blascovich, & Beall, 1999; Riva & Galimberti, 2001). Technological development offers immense opportunities for comparative inquiry.

Technology and Comparative Psychology

Beginning in the 1970s, nonhuman subjects became the "users" of technological systems (see Leighty & Fragaszy, 2003). That is, computers were no longer being used solely as response detectors or to control presentation of stimuli but were also presenting subjects with new environments in which to act. This work was pioneered with nonhuman primates by Duane Rumbaugh and his colleagues. Rumbaugh (1977) developed a visually based symbol system for the chimpanzee Lana by presenting lexigrams on a computerized keyboard. Presenting lexigrams in a computerized format allowed researchers to address symbol use in nonhumans in a new and more efficient way. The computerized presentation of lexigrams afforded Lana the opportunity to produce "words" and "phrases" when she desired, not just in response to a request by the experimenter, as was the case in alternative paradigms.

Lana later learned to manipulate a joystick to control the movement of a cursor on a computer monitor (Rumbaugh, Hopkins, Washburn, & Savage-Rumbaugh, 1989). Her ability, and that of other chimpanzees in the Rumbaugh lab, to "use" this form of interactive computer system allowed researchers to address a number of cognitive abilities such as numerosity judgments in a new way (Rumbaugh, Hopkins, Washburn, & Savage-Rumbaugh, 1993; Washburn & Rumbaugh, 1991a). Rumbaugh and colleagues also taught rhesus macaques and baboons to "use" these interactive computerized testing systems to study trajectory prediction, path planning, discrimination, categorization, mental rotation, and learning set performance (Hopkins, Fagot, & Vauclair, 1993; Rumbaugh, Richardson, Washburn, Savage-Rumbaugh, & Hopkins, 1989; Washburn, 1992; Washburn, Hopkins, & Rumbaugh, 1989; Washburn & Rumbaugh, 1991b; Wasserman, Fagot, & Young, 2001). Not only does this methodology allow subjects considerable latitude in how and when they interact with the experimental tasks, but it also provides a "level playing field" for cross-species comparisons (see Hopkins, Washburn, & Hyatt, 1996; Washburn & Rumbaugh, 1992). Because nonhumans "use" the interactive computerized testing systems as humans do, more direct comparison of nonhumans with humans is supported.

The development of this new method of cognitive inquiry has had far-reaching impacts on comparative psychology. Inspired by the approaches of Rumbaugh and colleagues, Tetsuro Matsuzawa developed an interactive computerized testing system in his laboratory at the Primate Research Institute in Inuyama, Japan. As does the Rumbaugh laboratory, Matsuzawa and colleagues address the ability of chimpanzees to work with numbers, as well as short-term memory and visual figure discrimination, and have furthered the investigation of path planning using touch-screen testing systems (Iversen & Matsuzawa, 2001, 1996; Kawai & Matsuzawa, 2001; Matsuzawa, 1985; Tomonaga & Matsuzawa, 1992).

We believe that interactive computerized testing systems have revolutionized comparative psychology, especially with nonhuman primates. They allow the subject to play an active role in the testing environment and permit a wide array of actions. These systems moved experimental approaches away from single response and choice tasks and allow us to examine cognition in nonhumans in a wide array of situations while still affording rigorous experimental control.

As we all know too well, technology advances at a rate that seems at times to exceed our ability to keep up with it. We fight to maintain the computerized testing systems of our laboratories by updating hardware and software and attempting to maintain compatibility. Many of us who examine cognition in nonhumans are wary of deviating from our established systems, knowing the difficulty of training animals on new interfaces and knowledgeable of the potential domino effect caused by changing one piece of equipment. Yet, we cannot let these attitudes hinder the development of our field. We can look to the booming progress in human cognitive research to see our future.

Interactive Virtual Reality

We are all familiar with the astonishing advances in neural imaging capabilities. However, another less recognized technology, the creation of virtual environments, is also poised to become a powerful ally in the quest to study perception and action. This new technology is known as *virtual reality* (VR), which refers to the use of computer graphics and peripheral devices to simulate a realistic-looking and -feeling world. This simulation is dynamic in that it responds to the inputs of the user and does so in real time. A real-time interaction between user and environment is a defining characteristic of VR (Burdea & Coiffet, 1994). Contributing to the realism of the VR environment is the fact that it may be achieved through multiple senses. In its most developed form, not only is the environment seen, but it is heard, felt, and occasionally smelled and tasted. VR thus provides an interesting leap in the application of technology to the experimental environment. Prior to the introduction of the virtual environment, computerized presentations were made in two dimensions. VR technology allows us to create the perception of a three-dimensional world.

What are the defining features of VR? How is it different from other computer simulations? Burdea and Coiffet (1994) referred to the defining features as the "three *I*s" of VR. The first of these is the *interactive* nature of the VR environment. That is, the environment responds to the user's actions. The second *I* refers to the idea that the VR environment is *immersive*, meaning that it affords perception of something that otherwise would not have been perceived without this external stimulation (Sherman & Craig, 2003). The third *I* is *imagination*, the only thing that limits the applications and functions of VR.

There are a number of different methods for the presentation of virtual environments to human participants. One often-used presentation device is the head-mounted display. The device works by presenting a pair of images on screens inside a pair of goggles or glasses, such that one image is viewed by each eye. Sensors are included within this system that track the movements of the participant's eyes and head to determine where in the image the participant is looking. Using this information, the computer alters the display to immediately reflect changes in viewpoint due to eye and head movements (Sherman & Craig, 2003). A second presentation method involves the participant being positioned in a room and surrounded by computer-generated displays. One example of such a presentation is the Cave Automatic Virtual Environment (CAVE) system developed at the University of Illinois (Sherman & Craig, 2003). One benefit of the CAVE system is that it allows for mobility of the participant and continually updates the projected images to reflect these movements.

These presentation methods are each strictly visual in form but can be augmented to provide stimulation to other senses. Sensors can be placed on the body to track movement through space. Automated systems insert sounds and odors into the virtual environment. Participants can wear receivers about the body to stimulate the touch receptors. This is most commonly conducted using a DataGlove (U.S. Patent No. 4,542,291; Zimmerman, 1985), which detects movements and force and provides pressure stimulation on the hands to simulate grasping and touch (Burdea & Coiffet, 1994).

Researchers of human cognition and perception have begun to present virtual environments in their laboratories to address a wide variety of experimental questions. They have discovered that the use of these interactive three-dimensional environments, in which behavioral responses of the participants are detected and recorded automatically, offers options for research never before available (Gaggioli, 2001). Early applications of VR were conducted by human performance researchers, often in conjunction with government projects. The most well known of these applications were flight simulators for the NASA program (Gaggioli, 2001). VR systems were soon introduced into psychological laboratories in the years following these early government projects. The areas of study to which VR has been applied are numerous and include perception (visual, haptic, etc.), visuospatial navigation, sensorimotor transformations, attention, memory, cognitive performance, and mental imagery (Gaggioli, 2001).

To give a few examples of the utilization of VR systems, researchers of human visual perception investigated the influence of optical flow on the perception of walking speed (Durgin & Kearns, 2002; Kearns, Durgin, & Warren, 2002). This same laboratory has also investigated the impact of vestibular and proprioceptive variables on path integration in the virtual environment (Kearns, Warren, Duchon, & Tarr, 2002). Fajen, Beem, and Warren (2002) had participants navigate through a virtual room of obstacles to study route selection in simple and complex environments. Harrison, Warren, and Tarr (2002) examined path selection in a virtual hedge maze while manipulating path form, landmarks, and path junctions. Sandstrom, Kaufman, and Huettel (1998) studied sex differences in the use of landmarks and room geometry in navigating a virtual water maze. Similarly, Gron, Wunderlich, Spitzer, Tomczak, and Riepe (2000) used the VR system and functional magnetic resonance imaging to identify the brain areas activated in navigation tasks and how activation in these areas differs by sex.

Integrating a haptic/force-feedback system into a VR application, Triesch, Sullivan, Hayhoe, and Ballard (2002) examined the propensity for change blindness (nondetection of changes within one's environment) in a reaching task. Researchers had the participants pick up objects within the virtual environment and place them on conveyer belts. On probe trials, the size of the object was altered between the time of picking it up and placing it on the conveyer belt. Participants were more likely to detect size manipulations if size was attended to in the sorting task (i.e., the objects were to be placed on conveyer belts by size). These findings emphasized the fragmented nature of attention, in that information of object features is often not noticed unless relevant to the particular task at hand.

These experiments exemplify some of the benefits of conducting research using VR systems in human perception and cognition. The first of these benefits is improved ecological validity (Gaggioli, 2001). Immersing the participant in the three-dimensional virtual environment can increase the ecological validity of the testing scenario over two-dimensional interfaces by creating a testing environment more comparable to that of the real world. Similarly, the researcher can place the participant in any number of virtual environments without leaving behind the control of the laboratory. The virtual environment is created by the researcher and thus is enormously flexible (Gaggioli, 2001). In this way we can accommodate for historical and subject variables in a way never possible before. The virtual environment allows the researcher to collect behavioral responses of all forms. It also affords action as we see in the real world (e.g., turning the head, walking, reaching), and the technology of the virtual environment ensures that these actions are detected and recorded. Another benefit of the applications of VR systems is the ability to provide participants with sensory feedback about their actions (Gaggioli, 2001). This feature, like that of the inclusion of normal movement in three dimensions, contributes to the ecological validity of the experimental setting and therefore the generalizability of the results.

Overall, the use of VR holds great promise as a revolutionary method of examining perception and cognition in humans. If this is the future of human perceptual and cognitive research, then we should also consider its applications for comparative psychologists. We propose that the integration of VR systems into laboratories of nonhuman cognition and perception will allow us to better examine continuity of cognition across species. This method will also increase the ecological validity of our experiments with nonhuman subjects in a similar manner as it does for human participants. In this way we can "remove" subjects from the laboratory setting and "insert" them into the virtual environment of our choosing. Once the subject is immersed in the virtual environment, we are able to observe an entire repertoire of behaviors that perhaps would not otherwise have been expressed in the laboratory.

The Promise of Virtual Reality

Imagine for a moment the possibilities for research that integrates VR into the nonhuman laboratory. We could examine kin recognition, food selection, predatory responses, response to social and behavioral cues, object recognition, locomotion, path selection, and numerous other areas of perception and cognition. We could immerse subjects in interactive environments of our own design while systematically controlling all the variables presented within the environment.

For example, consider research that has been conducted with nonhuman primates on path selection in mazes. This research was originally conducted by presenting a bird's-eye view of the maze on a two-dimensional computer screen, much like a paper-and-pencil maze. Subjects manipulated a joystick to navigate a cursor from the start point to the goal region (Fragaszy, Johnson-Pynn, Hirsh, & Brakke, 2003; Washburn & Astur, 2003). The perceptual nature of this task is far removed from that of moving oneself through a three-dimensional maze, because the actor can see the entire maze at each choice point. Washburn and Astur (2003) advanced this methodology by presenting rhesus macaques with two-dimensional mazes from the perspective of the subject (like that of contemporary video games) instead of the overhead or bird's-eye view. This alters the demands of the task by incorporating the subject into a three-dimensional environment. The study of navigation through a virtual hedge maze by human participants exemplifies the potential of the applications of VR by comparative psychologists (Harrison et al., 2002). By using the VR technology being developed by human cognition researchers, we will bridge our fields such that we can truly study the continuity of cognition using methods that address the importance of ecological validity and perception.

A number of technical and methodological problems arise when presenting virtual environments. Although in some ways VR can increase the ecological validity and generalizability of results compared with other laboratory testing methods, the degree of relatedness between perception and action in the virtual and actual environments has yet to be determined. We therefore cannot make broad generalizations from VR research. Other problems center on the fact that current sensory feedback systems are quite basic in form (especially in the case of proprioception), are still rather expensive, are not very portable, and are not easy to install or use without special training. However, with time, all of these issues will undoubtedly be mitigated if not fully resolved.

Challenges to Overcome

A number of logistical troubles must be resolved before we can integrate VR into studies of nonhuman cognition and perception to the degree it is used in studies with humans. The first and perhaps most obvious trouble spot will be the presentation method. How does one get an ape, monkey, pigeon, or rat to wear a headset and not remove critical wires and sensors? This is an excellent question, but we do not believe that it is an unsolvable problem. Many potential solutions exist, and we will only be limited by our own imaginations. Animals may be habituated to helmets, jackets, or gloves; certain motions of animals could be restricted (to prevent wire removal); or the CAVE-style setup could be chosen over the headset. We should also consider the pace at which VR technology has advanced over the past several decades. It is probable that miniaturized VR apparatus and remote detection devices will be developed in the near future, thus reducing the impracticality of application of current VR procedures with nonhumans.

A second issue that arises with the application of VR to nonhumans is a perceptual one. Much experimentation will be required to determine the degree to which the virtual and three-dimensional environments are equated (i.e., we must ask subjects if the virtual environment looks real). Additionally, we must consider the sensory feedback systems that we use with nonhumans. We will have to closely examine the perceptual systems of our subjects so that we can design appropriate virtual environments and feedback systems. Thus, a number of basic research issues of environmental perception by nonhumans, such as rapidity of eye movements, will need to be addressed prior to exposing them to virtual environments with the goal of simulating experiences in the real world.

Conclusion

The advances in technology witnessed over the past 50 years have provided researchers with many new tools for studying cognition across species. The innovative ways researchers have utilized these advances have had, and will continue to have, a profound impact, not only on the speed and efficiency with which research is conducted but, more important, on the questions and issues in comparative cognition that can be addressed. There are still some obstacles to be overcome before the use of leading-edge technologies like VR begin to flourish in the comparative arena, but at the rate technology is advancing we can already see their potential impact on the "virtual" horizon.

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