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COMMENTARY

Katherine A. Leighty · Dorothy M. Fragaszy

Primates in cyberspace: using interactive computer tasks to study perception and action in nonhuman animals

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In the scientific enterprise, to a larger extent than we might like to think, our measurement instruments define the questions we can ask. Centuries ago, the telescope and the microscope opened new universes for human inspection. More recently, particle accelerators enabled physicists to explore the structure of the atom. Today neuroimaging techniques such as FMRI (functional magnetic resonance imaging) have altered the questions that we can ask about neurological functioning. In experimental studies of behavior in nonhuman animals, numerous apparatus developed by ingenious investigators over the past century (e.g., Thorndike, Yerkes, Kluver, Tinklepaugh, Tolman, Crawford, Hayes and many others) provided new ways to study animal "intelligence" and learning. We are currently in the midst of another wave of technological innovation in which expanding use of digital technology is the agent of change. This wave of innovation will open new vistas in behavioral studies as surely as neuroimaging has done for neuroscience.

The computer has dramatically widened our methods of investigating comparative cognition in nonhuman species. Prior to the appearance of the desk-top computer, Skinner and others adapted mechanical and electronic recording and dispensing mechanisms to automate intertrial timing, delivery of reinforcers and data recording in experiments with rats and pigeons. The first contribution of computers to comparative cognitive research was primarily to automate even further the functions previously handled by electronic timers and counters. The devices also served as a storage mechanism for our expanding data sets and enabled us to conduct more detailed analyses of our data sets. In addition to these assistive uses, investigators increasingly exploited computerized systems to present experimental problems to subjects that otherwise would have been presented by using other forms of two- or three-dimensional (2D or 3D) displays. In most testing situations, the computer now serves as a means of presenting a display and registers the subject's response (a choice; a latency). In this case, the subject acts on the basis of the display, but it does not interact with the system itself; the subject does not "use" the system. Although quite practical, none of these uses of the emerging technology actually changed the questions experimenters addressed in their studies.

As the behavioral research community's familiarity and "comfort" with computers has increased, we are starting to use computers in a broader way in our research. We view the emergence of interactive paradigms in computerized research protocols as the next wave of methodological innovation in animal cognition. This work was pioneered with nonhuman primates by the research teams of Duane Rumbaugh (Richardson et al. 1990; Rumbaugh et al. 1991) and Tetsuro Matsuzawa (Tomonaga and Matsuzawa 1992; Iverson and Matsuzawa 1996, 2001; Kawai and Matsuzawa 2001). In essence, in these paradigms, the nonhuman subjects have become system "users."

To appreciate how this different perspective allows us to ask new questions, consider the burgeoning literature using "virtual reality" in humans to study topics such as optical flow and path integration (Kearns et al. 2002), navigation and steering behavior (Fajen, 2001), spatial updating (Wang et al. 2002), and change blindness (the inability to notice scene changes) (Triesch et al. 2002). We take it for granted that humans can act in virtual spaces, and (perhaps gratuitously) we assume that actions in virtual (2D) environments inform us about actions in physical (3D) environments. We are just beginning to study nonhuman primates as "users" or actors in virtual reality situations (see Washburn and Astur 2003).

Investigators working with birds, and coming from a different theoretical and methodological community, have begun to explore visual perception in the virtual environment. One example of such work is the discrimination of types of object motion (Cook et al. 2001). These investigators questioned whether pigeons could discriminate between optical flow fields simulating an object moving through versus around an object. The pigeons were able to

K. A. Leighty (✉) · D. M. Fragaszy
Department of Psychology, University of Georgia,
GA 30602–3013 Athens, USA
Tel.: +1-706-5428966, Fax: +1-706-5423275,
e-mail: kleighty@uga.edu

make this discrimination and transfer it to novel objects. To determine if the subjects were using 2D cues or a 3D representation of the event to solve this task, the authors introduced trials in which the frames where ordered in a random fashion. Pigeons were unable to solve the task in this condition. Cook et al. (2000) interpreted their findings to indicate that the birds were forming a 3D representation of the event rather than relying on 2D cues from the images. This is an important piece of information validating the use of 2D displays to study visual perception in pigeons. We do not yet have equivalent data for nonhuman primates.

In this set of papers, we present a sampling of several different research programs in which nonhuman primates "use" computers to solve problems. Studying how they do so offers a new and alternative window on cognition well beyond the familiar window of a perceiver making a choice. Leighty and Fragaszy (2003) begin by examining how capuchin monkeys (*Cebus apella*) learn to manipulate a joystick to bring a cursor in contact with a goal region on a monitor. Controlling a joystick requires learning several things about the relation between one's movement and cursor movement, as well as the relations among the cursor position, the goal region, and the endpoint of the task. Leighty and Fragaszy consider the learner's means of detecting the relevant relations, such as the link between the direction of arm movements and cursor movement, and the incorporation of visual tracking and body-tilting into action as mastery improves.

Using the same joystick-mediated testing system, Fragaszy et al. (2003) address the strategies used by capuchin monkeys and chimpanzees in navigating two-dimensional mazes with multiple choice points. Washburn and Astur (2003) investigate the navigational abilities of nonhumans in another form of cyberspace. They asked whether rhesus macaques (*Macaca mulatta*) are capable of perceiving and solving 2D virtual mazes that contained 3D features. In this experiment, the actor viewed the maze from the perspective of moving through it instead of the 2D plane view used by Fragaszy et al. (2003). The actor moved the joystick to change the whole display. Washburn and Astur (2003) simulate an object moving in a 3D environment by altering a 2D display to indicate walls, corners, depth, and so forth as the actor moves a cursor around the monitor.

The joystick-mediated system is not the only way in which nonhuman primates have "used" computers. Investigators have begun presenting interactive tasks with a touch screen interface. In this case the actor interacts directly, by manual contact, with the display. Iverson and Matsuzawa (2003) illustrate this method by investigating how chimpanzees learned to intercept a moving target using a touch screen system. This task required subjects to "drag" a disk to the moving target on the monitor.

McGonigle et al. (2003) sought answers to very different research questions by also using the touch screen system. They are concerned with how individuals learn to work with multiple items in efficient ways. In the study reported here, McGonigle et al. (2003) presented capuchin monkeys (*C. apella*) with a set of nine items on a touch screen monitor. The monkeys learned to touch each item in order by size (area). In one condition, all nine items were of the same shape. In a second condition the items were of three different shapes. This task allowed the monkeys to order their selections by shape (a class variable) and by size (a relational variable) within shape. The monkeys were able to work with both relative size and class membership in the same problem.

The five papers in this collection present research using two methods of interacting with a computer, the joystick and the touch screen. One may ask if the methods have differential utility. For example, the direct relation between action with the hand and movement of the cursor in the monitor would seem likely to privilege the touch screen method for tasks requiring precise movements (as in navigating around corners or through narrow apertures), and to afford quicker mastery of the system. Unfortunately, we do not as yet have data comparing performance by the same nonhuman species on the same tasks in the two interactive formats to answer questions about mastery and precision. While we have been working into using these two formats, interactive technology has been hurtling forward, so that now there are additional modes of interaction with computers. We are speaking of "Virtual reality" (the condition in which the user perceives a 3D environment composed by a computer; a "digital" environment.

The next step in comparative cognitive research will be to put animals "into" the 3D virtual environment. With humans, this is already done by wearing a special helmet (HMD, or head mounted display) so that the visual scene alters with eye movement, or wearing special gloves ("instrumented gloves") so that the actor feels virtual objects, or wearing earphones to hear virtual sounds, etc. (Stanney 2002). Instrumented gloves, for example, can present controlled forces to the user, allowing him or her to feel virtual objects as well as to control their motion (Turk 2002).

With virtual environment paradigms, we can provide a wider range of problems to our captive subjects, and (counterintuitively, at first glance) we may be able to simulate more natural settings for our subjects than we have in the past. For example, we could address the biomechanics of movement and postural adjustments in the virtual environment that might be impractical to present in real 3D (e.g., walking across an irregular surface, or reaching for a moving object). Further, we could examine performance in 4D environments (settings that provide stimulation to senses in addition to vision) if we can provide the instrumented devices to our nonhuman subjects.

Studying perception and action by nonhuman animals in virtual environments will allow us to address issues germane to our field, with additional beneficial consequences. It can keep our work integrated with the leading edge of work in other behavioral sciences, and it can increase our collaborative opportunities. For example, the artificial intelligence community is deeply interested in embodied cognition, and nonhuman animals provide thought-provoking variations on the human model for their work. Similarly, neuroimaging work is increasingly moving toward functional imaging (i.e., analyzing images taken over the course of activity). Current neuroimaging technology permits minimal movement by the subject during imaging. Virtual reality settings may provide a useful combination of interactive opportunity and spatial restriction during imaging. As another example, studies concerning coordination of eye movements during goal-directed action could profit from virtual reality testing paradigms. We could go on – it is easy to envision many uses of virtual reality technology to study perception and action in nonhumans, just as this technology is becoming increasingly useful in studies of human behavior.

Whatever the future brings, considering how agents act in two-dimensional and in virtual environments opens the way to new research paradigms in comparative cognition, and such techniques offer bridges to other fields of behavioral science. We hope this collection of articles will prompt others to think how they can use interactive paradigms in their research.

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