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Review

Designing for the exceptional user: Nonhuman animal-computer interaction (ACI)

Sarah E. Ritvo [a, *], Robert S. Allison [b]

[a] Department of Psychology, York University, Toronto, ON, Canada
[b] Department of Computer Science, York University, Toronto, ON, Canada

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A B S T R A C T

As sophisticated computer technologies become more affordable, flexible, and accessible, there is increasing interest in their application to nonhuman animals. A limiting factor however, is that traditional computer design has been anthropocentric. Animal factors have not driven the design of the majority of computer technologies that have, or could be applied to this user population. The anthropocentric nature of current hardware and software may act as a barrier for successful animal-computer interaction (ACI). In this review, the authors consolidate literature from diverse disciplines including psychology, computer science, human-computer interaction, animal behaviour and welfare, biology, ergonomics, medicine, human factors and disability studies to explore (a) how human-computer interaction (HCI) principles may apply (or not apply) to ACI, (b) how principles and computer system designs exclusive for ACI may be developed, and (c) how animal-centered computer designs may benefit HCI and its user population.

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* Corresponding author. York University, 4700 Keele Street, Toronto, ON M3J 1P3, Canada.
E-mail address: sritvo@yorku.ca (S.E. Ritvo).

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1. Introduction

Flexible, affordable, accessible and ubiquitous computing technologies, such as touchscreen interfaces and wearable computers, have been adopted for an ever-increasing range of human activities. Likewise, they have been increasingly used to enrich nonhuman animals' (more simply referred to as 'animals' in the remainder of this paper) lives as well. Hardware and applications are now explicitly being applied to, adapted and designed for domestic pets, farm animals, and exotic animals in captive facilities worldwide (Animal Behavior Associates, 2014; Cheok et al., 2011; Fernandez-Blance, 2012; Lee et al., 2006; Lucas, Toporoff, & Hoffman, 2014; Resner, 2001; Young, Young, Greenberg, & Sharlin, 2007). In the same vein, computer technology is also increasingly employed to study animal cognition (i.e., comparative cognition) (Hampton, 2014; Marsh & MacDonald, 2008; Ritvo & MacDonald, 2016; Schweller, 2012; Spetch, Cheng, & MacDonald, 1996; Vonk & MacDonald, 2004).

What is problematic, however, is that computer design has been primarily anthropocentric (designed for humans, by humans, from a human perspective, based on our understanding of human factors and the feedback gained from usability research on humans). In other words, by and large, animal factors (i.e., cognition, physiology, behaviour, etc.) have not determined the design of the vast majority of computer technology that has or could be applied to animals. In fact, despite the ever-increasing application of computer technology to the animal, very little research has been undertaken to determine how animal user experience differs from human user experience and how the design of computer hardware and software interfaces may be developed and optimized specifically for the animal user.

The purpose of the current paper is to explore how human-computer interaction (HCI) principles that have been derived from anthropocentric research and design may apply (or not apply) to animal computer interaction (ACI), how principles and computer system designs exclusive to ACI may be developed, and how animal-centered computer designs may benefit HCI and its user population.

2. Human-computer interaction (HCI) as a foundation for ACI

Human-computer interaction (HCI) is an interdisciplinary field that focuses on the study, design, implementation and evaluation of the interactions between human users and computer systems (Licker & Parker, 2003). This includes the computer system interface and the underlying computational and cognitive processes that generate human-computer interactions (Licker & Parker, 2003). Although the term *human-computer interaction* was first introduced in the 1980's by Card, Moran, and Newell (1983), HCI's roots can be traced back to earlier studies of human performance, ergonomics, human-machine interaction, and information science and technology (Dix, Finlay, Abowd, & Beale, 2004). HCI attempts to understand the way human users interact with computer technology so as to design systems that fluently satisfy users' needs (Benyon, Davies, Keller, Preece, & Rogers, 1997; Te'eni, Carey, & Zhang, 2007). To achieve these ends, HCI draws on multiple disciplines including computer science, cognitive science, human factors, software engineering, management science, psychology, sociology, and anthropology (Licker & Parker, 2003). Two of the most critical goals of HCI include usability and optimal user interfaces. Although conceived exclusively with humans in mind, as we will discuss, these goals also have considerable merit in application to animal users.

2.1. Usability

A primary goal of HCI is *usability,* defined as "the extent to which a given system with a given functionality can be used efficiently, effectively, and satisfactorily by specified users to achieve specified goals in a specified context" (Te'eni et al., 2007). In other words, how efficient, effective, sustainable, safe, accessible, easy to learn and useful is the system (Benyon, Turner, & Turner, 2005)? In the PACT framework, usability is concerned with achieving a balance between four elements of human-centered interactive design (Benyon et al., 1997, 2005):

- People (i.e., the user)
- Activities (i.e., the task or job)
- Context (i.e., the situation and environment)
- Technology (i.e., hardware and software)

Achieving this balance however is challenging because (a) each element influences the nature of user interaction both independently and in conjunction and (b) diverse users use computer systems for diverse purposes in diverse contexts (Benyon et al., 1997).

2.1.1. People (i.e., users)

Users are a heterogeneous group. They differ according to several factors that affect how they interact with a computer system, including: a) physiology (e.g., height, weight, handedness, visual acuity, dexterity, etc.) b) experience and knowledge (e.g., of computer systems, of the task they are attempting to accomplish, etc.) c) cognitive abilities (e.g., information processing, attention, memory, reasoning, decision making, etc.) d) psychology (e.g., sociability, pragmatism, patience, creativity, ingenuity, motivation, etc.) and e) socio-cultural influences (e.g., education, ethnicity, gender, social class, age, etc.) (Benyon et al., 1997). Therefore, to design effective systems, designers develop a detailed understanding of the intended user in terms of all of these factors through *user analysis* (Te'eni et al., 2007). With regards to ACI, user factors play a more essential and uniquely challenging role than in

HCI. Not only are animals a more heterogeneous population than humans (i.e., comprised of diverse species), but in addition, the distance between designer and user is inevitably more profound.

2.1.2. Activities (i.e., tasks)

Computers can automate physical and cognitive tasks, provide increased flexibility in performing tasks, or allow users to accomplish tasks that are otherwise impossible (e.g., simulating the effects of something that has not yet occurred) (Benyon et al., 1997). Accordingly, designers must consider whether the targeted task: a) is repetitive, b) is affected by environmental changes, c) occurs regularly, rarely, or concurrently d) requires specialized knowledge, e) is time sensitive, f) jeopardizes safety, g) involves unusual conditions (e.g., the user wears protective clothing or is disabled), g) is performed by a single user or a group of users, h) is one of many tasks that the user must switch between (Benyon et al., 1997). During the design of HCI systems, these characteristics are evaluated via *task analysis* (Te'eni et al., 2007). Computers can also enable animal activities and tasks; therefore task analysis is also important in ACI. However specific to ACI, (a) disambiguating the nature of animal activities and tasks may be difficult, particularly given the species-centric differences between designer and user, and (b) the ACI user may not be cognitively aware of their own tasks, goals, or specialized knowledge.

2.1.3. Context (i.e., setting)

The physical and social situation or environment in which HCI occurs also directly impacts interactive design. For example, cultural norms or personnel policies may constrain the user's behaviour, or a loud physical environment may make the use of audio communication impractical. *Context analysis* seeks to understand the situational, technical, physical, organizational, cultural and social settings where the systems will be used. With respect to ACI, this includes analysis of the diverse and complex cultural, organizational and social behaviours of the user species, subspecies and group, as well as the varied physical environments in which ACI systems may be employed (e.g., suburban homes, public footpaths, farms, zoos, aquariums, terrariums, etc.).

2.1.4. Technology (i.e., the system)

Both HCI and ACI designers must also take technical and logistical limitations into account during development. Technical limitations include available computer memory, hardware dimension and aesthetic requirements, as well as compatible input & output devices (Benyon et al., 1997). Logistic constraints include budgets, deadlines, staffing, and customer requirements (e.g., increased profits, publicity, productivity, physicality, amusement, safety, etc.).

2.2. The system interface

The system interface is the part of the system that the user engages with both physically and cognitively and consequently plays a large role in usability (Benyon et al., 1997). The system interface is literally the *face* of the system, acting as the medium through which a user communicates with the computer. Because users perceive the system through an interface, to a user, the interface and the system are one and the same (Te'eni et al., 2007). This perceived system-interface equivalence is even more pronounced for animals as they have no conception of computing and consequently, can only experience the system through its particular and immediate appearance, acoustics and actions.

Thus, the configuration of the interface strongly influences how users perceive and understand the functionality of the system. Accordingly, development, design and analysis of the user-computer interface is of primary importance (Te'eni et al., 2007). Optimal interfaces enable users to exploit the functions of the computer system to complete tasks in a way that is both intuitive and effortless (Benyon et al., 1997). In order to understand user-tasks and map them to system function, designers must again consider the PACT elements of user-centered interactive design (Benyon et al., 2005). Given the primacy of the interface for animal users, the mapping of function to goals/tasks/rewards is arguably even more crucial for ACI.

2.3. Why is HCI important?

Computer systems have the potential to be both extraordinarily beneficial and disastrously deleterious. On the one hand, computer systems have the potential for incalculable harm. Deficient systems can degrade quality of life, result in economic loss, bodily and/or environmental harm, and even death. Consider for example, the disastrous Air Inter Flight 148 crash in 1992. After a lengthy investigation, it was concluded "flight crew interaction with the aircraft" was likely a contributing factor to the crash (Paries, 1994). Particularly, the investigation concluded that the aircraft information displays did not provide adequate warning signals regarding the vertical position of the aircraft (Paries, 1994). On the other hand, exceptional systems also have the unique potential to make the world a better place. Computer systems have had remarkable positive effects on access to information, education, social action, equality and the expansion of knowledge. Superior computer systems with excellent usability can improve the user's safety, performance, capabilities and quality of life (Benyon et al., 1997). This is especially true in the case of systems designed for exceptional users (e.g., disabled humans, animals, etc.). Consider, for example, the facilitating impact of the tongue- and breath-controlled wheelchair for the quadriplegic population or the potential freedom, safety and independence afforded by accessible pedestrian signals (APS) (Harkey, Bentzen, Carter, & Barlow, 2009).

3. Nonhuman animal-computer interaction (ACI)

Animal-computer interaction (ACI) is a new and rapidly evolving field (McGrath, 2009). In fact, to our knowledge, the first deliberate attempt to apply HCI principles to the design of ACI systems was by Resner a little over a decade ago (Mancini, 2013; Resner, 2001). The first appearance of ACI at a CHI conference occurred even more recently in 2009 (Mancini, 2013). Similar to its HCI counterpart, ACI is an interdisciplinary field that involves the study, design, implementation and evaluation of species-specific computer interfaces that enable "a non-human to interact with a computer in a (species-specific) meaningful way" (McGrath, 2009). Because humans most often care for animals, humans are frequently involved in ACI to varying degrees as well (McGrath, 2009).

To fully appreciate the 'I' in ACI, it's important to distinguish between the terms *animal technology* and *ACI* (Mancini, 2013). Animal technology includes *any* technology intended for animals while ACI includes *only* those technologies intended for direct *interaction* with animals. For example, because it has been designed for use on animals, an automatic milking system (AMS) qualifies as an animal technology. However, a *voluntary* milking system on the other hand, qualifies as both an animal technology *and* an ACI system as it allows the animal to *self*-determine and *initiate* milking times via interaction with an interface. Ideally, ACI should purposefully and methodically consider and 'consult with' the target animal species during systematic *user-centered design* development (Mancini, 2013). In addition, akin to HCI, Mancini (2011, 2013) suggests that ACI should: a) study animal-computer interaction in naturalistic settings, b) develop user-centered systems that improve animals' lives, support animals' tasks and promote interspecies relationships and c) inform “a user-centered approach to the design of technology intended for animal use, by systematically explor[ing], adapt[ing] and evaluat[ing] theoretical and methodological frameworks and protocols from both HCI and animal science” (2013, p. 834).

3.1. Why is ACI important?

Like HCI, computer systems designed for the enrichment of captive and/or domesticated animals have the potential for significant positive effects. For decades radio and television have been employed to enrich captive primate facilities across the globe (Clay, Perdue, Gaalema, Dolins, & Bloomsmith, 2011; Lutz & Novak, 2005). But with the increased quantity, accessibility and affordability of portable touchscreen and wearable computer systems, we have seen a marked interest in designing computer systems and applications exclusively for animals (Ackerman, 2012; Cheok et al., 2011; Fernandez-Blance, 2012; Ioannou, Guttal, & Couzin, 2012; Lee et al., 2006; Lucas et al., 2014; Mancini, Harris, Aengenheister, & Guest, 2015; Mancini et al., 2014; Neustaedter & Golbeck, 2013; Noz & An, 2011; Resner, 2001; Tan et al., 2007; Yonezawa, Miyaki, & Rekimoto, 2009; Young et al., 2007). ACI systems could be employed for environmental enrichment, entertainment, behavioural training, physical examination, veterinary procedures, therapy, cognitive testing, communication, protection and safety, husbandry, etc. Imagine for example, the domesticated animal that can call their human caretaker at work through the press of a pedal when he becomes lonely, anxious or senses danger, or the allergenic human user who can interact with their pet without direct physical contact. Imagine the convenience and potential economic benefits of wearable computers that indicate when livestock are fertile or are ready to be milked or sheared. Or, more extraordinarily, imagine the infant captive wild or dangerous animal that can be hand raised by humans through the use of an avatar (thereby simultaneously protecting the handler from harm, preventing the animal from association with humans and encouraging association with its own species) (see Fig. 1). The possibilities are many, and they remain largely untapped.

3.2. Prospective ACI technologies

3.2.1. Tablet computers

Due to the sophistication, quantity, affordability and accessibility of tablet computers, they have quickly become the digital device of choice for young and old alike (Parsons & Oja, 2013). Tablet computers are thin, handheld, and employ a touch interface (i.e., are primarily controlled by the user's fingers or a stylus rather than a mouse, keyboard, joystick, etc.) (Parsons & Oja, 2013; Roebuck, 2012). Most tablets are also equipped with Wi-Fi, web browsers, cameras, microphones, accelerometers, GPS, proximity sensors, and gyroscopes. These sensors and systems support natural interfaces such as voice (e.g., Apple's iPad Siri) and gesture recognition (Gruber et al., 2012; Parsons & Oja, 2013).

What is unique about tablets, when compared to laptop, desktop, and other conventional computer designs, is that the touchscreen serves as a display, writing pad, and drawing pad in one. Consequently, the user is not required to translate their physical motion into virtual motion through a mouse or another control device. Rather, the user can touch, drag, rotate and tilt the computer directly using his own extremities. This allows simpler response selection processing and overlap of perceptual and motor processing (Kieras, Meyer, & Ballas, 2001). Because animals naturally engage with their environment through unmediated, direct contact and manipulation, touchscreen interfaces are potentially more intuitive than a joystick or a mouse. Intuitive interfaces require less training and comprehension to use and therefore are aptly suited for the computer-naïve and/or cognitively impaired user (e.g., the elderly, children and animals) (Bolt, 1980, pp. 262–270; Ishii, 2008). Furthermore, the mobility and relative durability of tablets make them convenient for use in captive animal facilities in which there is often limited space to accommodate permanent nonessential installations.

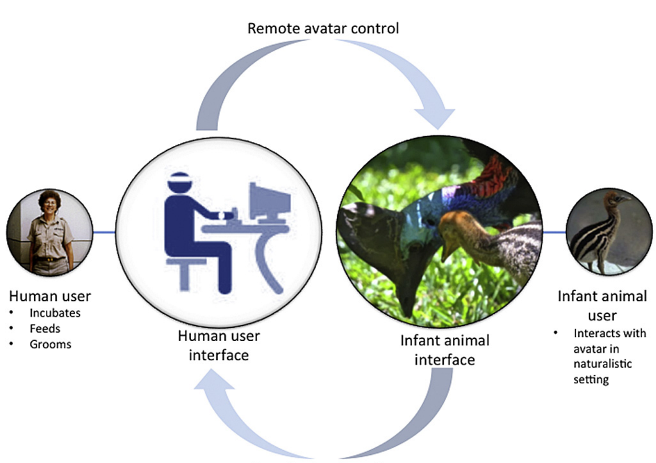

Fig. 1. Animal-human computer interaction concept for naturalistic care of infant captive exotic animals.

3.2.2. Wearables

Wearable computers offer many of the features of tablet computers, with the added benefit of greater mobility and increased interconnection between the user and the computer. Wearables provide both serendipitous interaction with the user (e.g., by offering unsolicited information based on the user's location or actions) as well as “constancy of interaction” (Mann, 2014). That is, wearables are always operating; the user does not need to turn the device on to engage with it. Furthermore, because wearables are worn on the body and are always running in the background, they allow the user to multi-task while engaging with the wearable (i.e., the user can engage the wearable computer while simultaneously performing other activities) (Mann, 2014).

Notably, the fact that wearables do not need to be held and that they do not require direct user-manipulation (i.e., they can operate independently and serendipitously without requiring to be turned on or directed) makes wearables aptly suited for use by computer-naïve and cognitively distinct users (e.g., children, the elderly and animals). Wearables allow animals “to move and act naturally, while receiving and sending information via computers” (McGrath, 2009) (see Fig. 2). Imagine for example, a wearable system that provides a canine user a food reward every time he performs a preferred behaviour (even outside the presence of their human owner), or that allows the canine user to “video call” their human owner at work if/when they enter a certain room in the home.

4. Existing ACI designs

Although by no means exhaustive, the following section provides a representative overview of successfully implemented ACI designs that are a) frequently referenced, b) designed for diverse application and species, c) operational and user-tested.

Fig. 2. An example of a wearable GPS-based computer system worn by cattle users (photo CSIRO/Wikimedia Commons/CC-BY3.0).

4.1. Remote human-pet interaction computer-mediated systems

The design of applications that extend human-pet interactions and communication has become a popular trend in ACI (Gabriel, Gershenfeld, Cerf, & Reiss, 2013; McGrath, 2009). For example, the Human Computer Dog Interface (Silver & Trudel, 2008), and Rover@Home (Resner, 2001) provide human and canine users a visual and auditory representation of one another that facilitates communication remotely through the Internet. Such ACI systems allow the human user to feed and interact with the canine remotely as well (Silver & Trudel, 2008). Rover@Home includes physical prop-interfaces, which the human user can verbally request the dog to touch. When the dog touches the requested interface, the system informs the human via their graphical display and automatically provides a reinforcing sound and food reward for the canine user (Resner, 2001).

A similar ACI system designed for feline users is Young et al.'s 'Feline Fun Park' (2007); described as a "computerized cat condo" that allows human users to remotely interact with their cats. Sensors in the interactive playground detect the cat's movement and actions, thereby allowing timely activation of automated toys and lights for the cat's entertainment (McGrath, 2009). The human user is simultaneously provided a visual display of the cat's activities via web cam and can interact with the cat user by remotely controlling toys and sensors (McGrath, 2009).

Designers have also ventured into the realm of cross-species computer games (Cheok et al., 2011; Clay et al., 2011; Tan et al., 2007). Cheok et al. (2011) have designed an online mixed reality computer game called *Metazoa Ludens* in which hamster users and human users play a virtual game of chase through their respective interfaces (Fig. 1). The human interface comprises a conventional visual display of a virtual world, complete with a human and a hamster avatar. The hamster's interface however, is a combination of a) a fluctuating 3D floor that is programmed to physically represent and correspond to the virtual environment and b) a robotically controlled bait to chase (Cheok et al., 2011). The human remotely controls the bait's movement (which in the virtual world is represented by the human avatar) and through this interface, the hamster user, who in the real world is physically chasing the bait, virtually chases the human avatar.

Not only is Metazoa Ludens an extraordinary example of human-animal computer mediated interaction, it also serves as an example of the importance and success of user-centered ACI design. Although a designer might assume that a suitable 'hamster bait' would be a preferred food item, after observing hamster behaviour and carefully considering the species, *Metazoa Ludens* designers concluded that food was unlikely to be pursued because hamsters are not a predatory species (Tan et al., 2007). Rather, the designers studied hamsters' inherent preferences and impulses, concluding that one of hamsters' strongest drives is to burrow in or under objects. Consequently, a small piece of tubing was efficaciously chosen as hamster bait—the hamster was inherently inclined to chase the small piece of tubing in an attempt to burrow in it.

4.2. Wearable computer systems (i.e., wearables)

Given wearable computers' suitability for animal users, several prototypes have been developed for various species (e.g., dogs, cows and chickens) (Beilharz, Jakovich, & Ferguson, 2006; Lee et al., 2006; Ping, Farbiz, & Cheok, 2003; Ping, Farbiz, & Cheok, 2004; Savage et al., 2000). For example, Lee et al. (2006), have developed a human-poultry computer interaction system. Through motorized vibrations in the wearable computer jacket, the chicken user experiences the sensation of being stroked by a human caregiver. To induce this sensation in the chicken, the human user physically strokes a chicken avatar and the sensory information is remotely transmitted and communicated to the chicken user through the wearable (Lee et al., 2006).

Savage et al. (2000) have developed a wearable system for service dogs called UNAM-CAN. This canine wearable gives the service dog audio commands through an embedded speaker. The design is intended to help the guide dog to perform complex tasks by breaking those tasks into simple, sequential, intelligible and practicable audio-delivered behavioural commands (Savage et al., 2000). This ACI system can allow the dog to perform tasks that he couldn't perform on his own (e.g., rescue, surveillance, guidance, menial tasks, etc.) (Savage et al., 2000).

However, effective animal wearables do not always require this level of complexity. Simpler designs have proven both functional and worthwhile. For example, Ladha, Hammerla, Hughes, Olivier, and Ploetz (2013) designed a collar-worn accelerometry system that identifies and records naturalistic dog activity (i.e., the frequency and variability of specified behaviours) as a means of welfare assessment.

4.3. Research-facilitating ACI systems

ACI systems are becoming increasingly employed in the study of animal cognition, physiology and sensory systems. In Dr. Suzanne MacDonald's lab at York University, touchscreen interfaces have been employed to study a myriad of cognitive capacities in captive apes, ranging from perceptual categorization to spatial strategies, and from visual preferences to music discrimination (see Fig. 3) (Marsh, Adams, Floyd, & MacDonald, 2013; Marsh, Spetch, & MacDonald, 2011; Marsh & MacDonald, 2008; Ritvo & MacDonald, 2016; Vonk & MacDonald, 2002, 2004). Computer-based graphic symbol systems have also played a critical role in investigation of ape language abilities. Manual keyboard-display and touchscreen systems have been employed to study the capacity of apes—including gorillas, chimpanzees and bonobos—to acquire arbitrary visual graphic symbols (known as lexigrams) as the equivalent of spoken words (Langs, Badalamenti, & Savage-Rumbaugh, 1996; Lyn, Greenfield, & Savage-Rumbaugh, 2011; Rumbaugh, 1977; Savage-Rumbaugh, 1984, 1986, 1991). Manual and touchscreen keyboards display hundreds of lexigrams that ape users associate with English words. Through this interface, ape users can 'talk' with human listeners by touching the appropriate lexigrams. A benefit of the touchscreen keyboard interface is that

Fig. 3. Budi, a Sumatran orangutan at the Toronto Zoo, makes music preference choices on a touchscreen interface (Ritvo & MacDonald, 2016).

new lexigrams can be easily added spontaneously by human conversation partners as the ape users learn new words. Furthermore, during training, images of the action, object or concept a new lexigram describes can be called up as an illustration (Schweller, 2012). Thus, touchscreen presentation offers considerable flexibility compared to facsimile and manual lexigram keyboards used in earlier studies of ape language acquisition (Rumbaugh, von Glasersfeld, Warner, Pisani, & Gill, 1974; Savage-Rumbaugh & Rumbaugh, 1978). Dr. Ken Schweller a former colleague of Dr. Savage-Rumbaugh at the Great Ape Trust in Des Moines has expanded this language app design to tablets for bonobos (Schweller, 2012). A tablet format offers an economical (i.e., replaceable) and convenient option for delivery. He anticipates that tablets will eventually replace the need for bonobo users to touch individual lexigrams on their touchscreen keyboards and that "autocomplete" functions will expedite ape-human computer mediated communication (Hsu, 2012; Schweller, 2012).

Virtual reality ACI systems have also been developed to simulate particular environments in particular contexts, to observe or measure animals' behaviour and physiology under circumstances that could not be tested through other means (e.g., naturalistic behaviour in the wild). This type of ACI system provides naturalistic conditions but in an environment that is regulated enough to control for critical variables. Such an interface is often 'invisible' to the animal user, allowing it to interact with the system through spontaneous natural behaviour rather than deliberate interaction. Research using ACI systems can yield insights about animal behaviour, physiology health, and disease. For example, Takalo et al. (2012) created a VR ACI system for cockroaches that simulated a forest environment. The cockroach was placed in front of a large display and tethered to a wire on top of a foam ball that turned as the insect ran and that kept it imperceptibly afloat on a current of air. Movements of the foam ball were tracked by a computer system that translated the ball's movements into corresponding movements in the virtual environment. Consequently, the cockroach perceived itself walking through a forest allowing researchers to measure its brain activity as it did so.

Similarly, in David Tank's laboratory at Princeton, researchers designed a VR maze for mice-users (Harvey, Coen, & Tank, 2012). Mice ran on a spherical ball surrounded by a wide-angle screen. The movement of the ball was detected by optical sensors and used to update the visual display so as to simulate running through a virtual environment. Simultaneously, an infrared optical microscope was aimed at the mouse's head and used to visualize and record neuronal firing. Other researchers at Princeton have designed an ACI video game for bluegill fish (Ioannou et al., 2012). Moving red dots that represent prey are projected into the fish tank in different formations and patterns. This fish 'game' allows researchers to observe the effects of different prey movement formations and patterns on the hunting behaviour. Similarly, customized miniature 3D computer displays have been employed to simulate the prey of praying mantis' so as to study their visual capabilities and predatory behaviours (Nityananda et al., 2015).

5. Challenges in ACI design

Thus far, we have established the definition and importance of ACI as well as popular candidate mechanisms through which ACI may be delivered. However, the design and development of ACI systems face several theoretical, practical and methodological challenges. Primarily, the majority of current computer interface systems are anthropocentric (designed for humans, by humans, based on consideration of human physiology, perception, cognition and usability research results). In other words, as McGrath (2009) notes, most computer interactions are focused on human-centered (a) modes (e.g., human language interfaces, visual displays tuned to the human visual system and physical mechanisms tuned to human limbs) and (b) tasks (e.g., tasks that humans understand intuitively or through experience, and tasks that are based on human input and output). There is every reason to believe that each animal species (a) differs from humans and (b) differs from other animal species in terms of these factors. To further complicate matters, each nonhuman species is physiologically unique and most, if not all, cannot understand specific or detailed directions or explanation. Thus, the combination of the enormous diversity of animal species, the inability of animal users to receive instructions or provide explicit feedback, and the incompatibility of physical interfaces across species, makes the design of ACI systems more demanding in terms of the user-research required to design appropriate interfaces, the designer's time investment and the potential costs of manufacturing novel and unique physical interfaces.

5.1. Challenges related to ACI mechanisms

Unlike human users who have been trained both directly, and through socialization to use technological mechanisms in a certain way, animal users typically have not. To further complicate matters, given their distinct physiology, cognitive and sensory systems, a) they may be inclined to use ACI system mechanisms differently than humans, b) they cannot read a user-manual, c) they may not comprehend that they are using a computer system, and d) they are more difficult to train than human users.

Another significant challenge related to ACI mechanisms is the diversity of physiology, morphology, sensory systems, motor control, dexterity, etc. between species. Some species live in the air while some live in the water. Some species navigate via sound, some via sonar, and some via smell. Some species don't have dexterous limbs, while others have much longer and stronger dexterous limbs than humans. Some species are blind or deaf, while others see wavelengths of light and hear frequencies of sound that humans cannot. The list is long and bewildering. Even orangutans, a close human relative with nearly identical genetics and relatively similar physiology, display remarkably different behaviours and approaches in relation to computer systems than humans. For example, although orangutans have long, strong fingers, they rarely use their fingertips when handling objects, preferring to use their palms and knuckles instead. This can make interaction with sensitive touchscreen interfaces a difficult enterprise. Furthermore, as Wirman (2013) describes, in the presence of touchscreens orangutans have been observed exploring the screens with their tongues rather than their fingers, and appear more interested in supporting mechanisms and hardware than the display. The background research and observation of target-species is much more laborious and time intensive for ACI design than for HCI. Furthermore, ACI is likely to require the production of novel, diverse, flexible, or adaptable hardware systems and supporting mechanisms and thus may entail significant requirements for time, expertise, and financial backing.

5.2. Challenges related to ACI tasks & interfaces

In contrast to human users, with animal users, it is more difficult and sometimes impractical to convey an ACI task. As Wirman (2013) highlights, it's easy to tell a human user the *game* they are about to *play*, is for *fun*, thereby allowing the human user to adopt a playful disposition and attitude towards the interface. However, that is not so easy to do with an animal. A computer does not necessarily imply play to an animal. Although animals do have species-specific play initiation signals that could plausibly be incorporated into ACI systems, it may prove difficult to represent these signals in such a way that their subtlety and authenticity is preserved to an adequate degree (Wirman, 2013). Furthermore, animals may not conceive of ACI software (e.g., a tablet app) as 'play' at all. Orangutan play for example, tends to be very physical, (i.e., wrestling, chasing, throwing, etc.). An orangutan user, therefore, is less likely to engage in the "the focused and systematic one finger touchscreen play that we are used to seeing in humans" (Wirman, 2013).

To avoid the need for a manual or instructions the ACI "interface should reveal its functionality through its affordances" (Resner, 2001). That is, much like a hammer, form should follow function; an interface should intuitively encourage the animal user to interact with the system the way it was meant to be used (Mine, Brooks, & Sequin, 1997). This can be achieved by including affordances that are consistent with the animal's physiology, morphology, sensory systems and natural behaviour (Resner, 2001).

An ACI interface should also strive to bridge what Norman (2013) describes as the 'gulf of execution' or the degree of congruence between the user's intended actions and those provided by the system. That is, the interface should allow an animal user to directly and effortlessly interact with the system in a manner that is consistent with his or her expectations (i.e., is consistent with his or her cognitive model of the task - both innate and learned) (Norman, 2013; Resner, 2001). This is most readily achieved by founding the ACI task and interface on an established behavioural pattern (e.g., foraging). The ACI designer also cannot expect for the animal user to understand symbolism, or abstract visual images and displays in the same ways humans do. The ACI interface can overcome this lack of understanding through *direct manipulation* (Hutchins, Hollan, & Norman, 1986; Ishii & Ullmer, 1997). That is, ideally the animal would be able to directly observe and physically move objects with his or her body. In the real world this implies that the interface should not confuse the ACI task, but rather should focus on the ACI task as precisely, evidently and transparently as possible (Resner, 2001).

Taking all of these task and interface challenges into account, Resner (2001) recommends that for optimal usability the ACI interface designer a) explicitly select an animal behaviour to be augmented, replicated or supported, b) provide transparent access to a task the animal seeks and c) ensure the result of the ACI is motivational to the animal user. This last requirement is made more difficult by the fact that many animals have greater difficulty in associating actions with outcomes. One method of fostering association between action and outcome that does not require behavioural training is to make the outcome of an action as instantaneous as possible (i.e., operant conditioning) (Skinner, 1963).

5.3. Challenges related to ACI ethics & user satisfaction

Evaluating usability and user satisfaction in ACI systems that involve both animal and human users requires consideration of the benefits and costs for all parties involved (McGrath, 2009). On the one hand, ACI can provide empirically supported advantages to both animal and human users alike (Lee et al., 2006; Resner, 2001). ACI systems can remotely provide humans and animals exercise, entertainment, distraction and comfort (e.g., human-canine computer mediated communication or interactive environmental enrichment systems for captive exotic animals) (McGrath, 2009). ACI systems that facilitate human-animal communication and play also have the potential to bring species closer together. Pierce and Bekoff (2009, p. 461) suggest that "play is a unique category of behaviour that tolerates asymmetries more than other categories of behaviour". Human-animal computer-mediated play provides an unparalleled opportunity for understanding, exploration, empathy, alliance, meta-communication and the equalizing of power relations between potentially asymmetrical species. Consider for example, the unequal power relations inherent in zoo settings in which animals are *placed* on *display* for humans' education and *entertainment.* RoboBonobo (Ackerman, 2012) attempts to invert this relationship by providing Bonobos at an ape sanctuary control over a robotic ape that can chase and shoot guests with a water gun. Although inclusion of weaponry is questionable, not only does an ACI system for captive animals like this one provide interactive recreation for human users and animal users alike, but they also afford the opportunity for animal users to *choose* the type, quality and duration of interaction with humans who visit them. This type of ACI system thereby provides the animal a degree of control and power over their environment that they would not normally possess. Human-animal intimacy fostered by these types of ACI systems also has the potential to increase popular concern for the user-species and their natural habitat, thereby endorsing pro-animal conservation and activism. On a more practical level, ACI systems can also provide a means for the human caregiver to remotely monitor the health, safety, behaviour and activity of animals in their care (McGrath, 2009). Furthermore, Savage et al.'s (2000) service dog wearable demonstrates the potential for enhancing service animals' ability and applicability, thereby also enhancing the independence, inconspicuousness, health and safety of the humans they service. Imagine the potential for service animal wearables that also monitor the health of the humans they assist (Savage et al., 2000).

On the other hand, however, there are also ACI systems that bring about a) questionable benefit, and b) potential harm to the animal user. These ACI systems all too often suffer from anthropomorphic design. Take for example, the Sensor Cow (Beilharz et al., 2006) that allows human and animal users to dance with one another to improvised music. Needless to say, although entertaining to the human user, the entertainment or other value to the cow user is questionable at best. This raises the question of what animals *like to do* and how user satisfaction can be measured. This is further complicated by the fact that animals cannot verbally give or withdraw their consent to participate in ACI research and with ACI systems. For example, do hamsters *like* to "play games" like Metazoa Ludens with humans? Do fish? How can we tell? Would an animal withdraw from an ACI game if they did not enjoy it? Would an animal necessarily continue to play an ACI game if they did enjoy it? What does 'enjoyment' and 'liking' look like in the user species? Unlike in HCI, in ACI, commonly used methodologies for analysis of usability and user satisfaction (e.g., questionnaires, self-reports, etc.) are not feasible with animals (McGrath, 2009). Furthermore, inferring mental states from spontaneous animal behaviour (e.g., facial expressions) is subject to confounding misinterpretation and anthropocentric bias (see Fig. 4). Even the wagging tail of a dog, customarily understood as a sign of happiness has, under scrutiny, been found to be a far more complex and varied barometer of canine emotion than anticipated (Quaranta, Siniscalchi, & Vallortigara, 2007).

ACI designers have started to address this issue through novel assessment methods. Those that do not rely on subjective human interpretation of the animals' user experience, tend to rely on various measures of animal-users' 'preference'. In these paradigms, preference is signified by choosing an item or condition over another based on either a) *liking* one object/condition more than another, or b) *disliking* one object/condition less than another. Lee et al. (2006) for example have attempted to evaluate a chicken's user experience of its wearable computer jacket by allowing the chicken, over a period of four weeks, to choose to spend time in one of two available cages. Only when the chicken is in one of these cages will he be dressed in the wearable. To make this user experience assessment more rigorous, the researchers weighted the push doors at the entrance to the wearable cage, thus requiring more effort on the part of the chicken to enter the wearable cage as opposed to the neutral cage. Similarly, Cheok et al. (2011) assessed hamster user experience of the Metazoa Ludens by carrying out a preference study in which the hamster could initiate or end participation in the ACI game. These researchers further attempted to assess the effects of the ACI system on hamster users through a six-week controlled health study.

Fig. 4. A classic illustration from Darwin (1872)'s *The Expression of the Emotions in Man and Animals* illustrating the author's interpretation of a chimpanzee's 'mood' based on facial expression. Such interpretations across species are challenging and potentially problematic (see section 5.3).

Although these animal experience assessment methods are both laudable and promising, more work is needed in this area to assess the validity and reliability of these measurements as well as to investigate alternative means of animal user experience assessment (Ritvo & Allison, 2014).

6. Learning from design for other exceptional users: HCI for the disabled

Although research in ACI is gaining momentum, as illustrated above, the discipline also faces many challenges. Solutions to these challenges may be found in other exceptional forms of user-computer interaction. According to the World Health Organization's International Classification of Functioning, Disability and Health (known commonly as the ICF) (2002), disability is an umbrella term that includes impairments, activity limitations, and participation restriction. The ICF defines *impairments* as "a problem in body function or structure" (WHO, 2002, p. 10). In other words, 'impairments' refers to parts or systems of the body that do not function the same way as those of able-bodied humans. In the ICF framework an *activity limitation* is defined as "difficulties an individual may have in executing activities" (WHO, 2002, p. 10). In other words, 'activity limitation' refers to activities an individual cannot do as a result of how they differ from the prototypical able-bodied human. Finally, the ICF defines a *participation restriction* as "problems an individual may experience in involvement in life situations" (WHO, 2002, p. 10). In other words, 'participation restriction' refers to the ways in which differing from an able-bodied human limit an individual's capacity to participate in certain activities and situations. When we consider the ICF description of disability from this perspective, the similarities between disabled humans and animals in relation to interface design is noteworthy. Similarly to a disabled human, an animal suffers 'impairments', 'activity limitations' and 'participation restriction' with regards to the use of computer interfaces as a result of the ways in which its physiology, body functions, cognition, behaviour and sensory systems differ from those of able-bodied humans.'[1]

It is estimated that at least 10% of the global population has a disability that will affect their interaction with computers (Dix et al., 2004). Consequently one would hope that research and theory targeting HCI for disabled users might offer guidance in regards to suitable ACI methodologies and effective design. However, similar to the case of animals, addressing the user needs of the disabled human population has been given significantly less attention in HCI research than that for able-bodied counterparts. System designers tend to see themselves and their colleagues as the prototype of the system user. This can result in the disregard of exceptional users' experience (Bergman & Johnson, 1995, pp. 87–114). As recently as 1986 and 1987 at the UK's *HCI* there were no papers that focused on interfaces for disabled individuals. Although the American CHI conferences of 1986 and 1987 included some discussion of human interface design for disabled users, attention to the needs of disabled users was still comparatively small (Edwards, 1995). Although HCI for users with disabilities is still a burgeoning field of study itself, it nonetheless predates ACI and has

[1] Of course, it is important to note that both animals and the 'disabled' may also possess superior abilities to the average human (i.e., strength, speed, perception, etc.).

valuable insight to offer with regards to ideas, themes, and challenges common to both disciplines.

6.1. Designing for disabled users: take away messages

6.1.1. Avoid binary distinctions

Edwards (1995) astutely identifies that there is a basic error in considering an exceptional user population dualistically (i.e., abled vs. disabled, or human vs. animal). In doing so, it simultaneously groups, minimizes and simplifies the wide range of characteristics in both groups (McGrath, 2009; Vanderheiden, 1990). Consider, for example the 'International Symbol of Access': a wheel chair-bound stick figure (Ben-Moshe & Powell, 2007; Edwards, 1995; Powell & Ben-Moshe, 2009). Although an effective symbol of disability, it is not a *model* of disability. Rather, disabilities requiring a wheelchair represent only a small fraction of a gamut of incapacities (e.g., physical, cognitive, sensory, emotional). Furthermore many people have a combination of disabilities, or only partially meet the definition of a single disability (Waller, Williams, Langdon, & Clarkson, 2010). In considering animals, just as there are varying degrees and types of disability, there are a multitude of species and sub-species that differ from humans in various respects and to varying degrees. Binary classification systems (i.e., able vs. disabled, or human vs. animal) ignore the range of physical, sensory and cognitive abilities in the latter groups (i.e., disabled and animal users) and assumes more similarity in these groups than is warranted (Edwards, 1995; Soares, 2012; Vanderheiden, 1990). This can lead to computer interaction designers and researchers subscribing to too narrow a view of the exceptional user population. Even wheelchair-bound users have as large a range of abilities (i.e., physical, sensory, cognitive, etc.) as any other user group. In fact, their only shared characteristic is for the most part, the use of a wheelchair (Edwards, 1995). This consideration is even truer with respect to animals. Between species, animals' only shared characteristic is that they are *not human*, an indiscriminant disparate grouping variable.

6.1.2. Adaptation vs. re-design

As opposed to re-design (i.e., prostheses), *adaptations* enable exceptional users to use hard- and soft-ware for the same purposes as conventional users (Edwards, 1995). The adaptation provides an intermediate interface that enables the atypical user to use a standard interface. To do so, it must act as an intermediary, interfacing with the user on one side, and with the application on the other. For example attachable touchscreen interfaces are commonly used in ape ACI (Marsh et al., 2011, 2013; Marsh & MacDonald, 2008; Ritvo & MacDonald, 2016; Vonk & MacDonald, 2002, 2004), enabling apes to interact with a computer via direct physical manipulation (i.e., with their fingers) as opposed to via typical indirect manipulation (i.e., with a mouse). The advantage of an adaptation as opposed to a prosthesis is clearly evident; a single adaptation may be effective for a range of applications (e.g., an attached touchscreen enables apes to use a wide range of standard human-intended computer hardware and software). Furthermore, the economic benefits of a single accommodation are twofold: the manufacturer only need develop a single adaptation, and the user only need purchase a single product (Edwards, 1995; Vanderheiden, 1990).

However, although ideally an adaptation will seamlessly fit both the user and the application, in practice, a perfect fit is unlikely. Rather, some aspect of the original standard interface will not be translatable or accommodated by the adaptation, making the exceptional user's interaction with the application flawed in some way (Edwards, 1995). For example, inaccuracy and lag are often an issue with attachable touchscreen interfaces used in ape ACI. Consequently, the interaction between the exceptional user and the standard interface (via an adaptation) is likely to be more problematic and difficult than it is for the standard user. For animals whose motivation to interact with computers may be precarious to begin with, this can be extremely problematic (e.g., inaccuracy and lag frustrates and confuses ape-users, increasing the likelihood of misunderstanding of the software program or withdrawal from the interaction).

Alternatively, a prosthesis, unlike an adaptation, is designed with a single individual in mind, and *their* particular type and degree of deviation from the standard user. This frees the re-designer from any constraints inherent in a standard application, affording a more direct fit between the user and the application and consequently a less problematic and effortless interaction between an exceptional user and an exceptional interface.

In the case of disabled users, of the two options mentioned above, adaptation appears to be favored. Not only is it economical, but it also offers advantages in terms of (a) compatibility within an organization (i.e., for file sharing between colleagues, etc.), (b) diversity and choice (i.e., a wide range of existing applications can be adapted, rather than obliging the exceptional user to rely on a single application) and finally, (c) self-esteem (i.e., the disabled user is less conspicuous) (Edwards, 1995). Although self-esteem may not be relevant for animal users, costs, compatibility within an organization, diversity and choice are relevant and make adaptations an appealing option for ACI as well. However the interaction costs associated with adaptations (e.g., inaccuracy and lag) must also be considered.

6.1.3. Involve the user

Although in all interface design it is highly recommended to involve the user in both development and testing, this is especially true of interface design for the exceptional user. Not only are designers liable to wittingly or unwittingly use themselves as the prototype user of the system, but even conscious attempts to design for the exceptional user can miss the mark. Designers who are not disabled themselves, are susceptible to designing what they *believe* users need, rather than what the user himself really *desires* or *requires* (Abascal, 2002; Soares, 2012). For example, it is difficult for the able-bodied designer to anticipate some of the aspects of technology that are obvious to a disabled user (e.g., the use of headphones by a blind user, obstructs hearing, a sense employed for orientation, travel and communication) (Edwards, 1995). In effect, someone who has never been disabled in the same way or to the same degree as their intended client is unlikely to consider many variables that are crucial for the disabled client themselves (Abascal, 2002; Edwards, 1995; Lueder, 2008). Given the potential for this gulf of understanding between members of the same species, imagine the designer charged with creating an interface for a Capuchin monkey, an animal who differs from him physiologically, cognitively *and* behaviorally. How might he possibly anticipate the interface-factors relevant to a user so different from himself?

However, consulting with the user is often not sufficient (i.e., as in the case of disabled users) or not possible (i.e., as in the case of animal users). Humans are surprisingly inept at explaining *how* they do the things they do, particularly when it comes to mental activities (Dix et al., 2004) and most animals are not capable of reliably communicating with humans. For this reason, it is critically important to watch the user as they *do* (e.g., chimpanzees 'fishing' for termites) and to study the things they *use* while do*ing* (e.g., long sticks) (Dix et al., 2004). Observation, in the case of humans, also allows the user to explain *why* they did what they did in retrospect (even if they were not aware of it at the time, or their subjective explanations are not entirely accurate) (Dix et al., 2004). Animal observation on the other hand, might include frequent and early prototyping or ethnographic and experimental studies to test assumptions regarding target species behaviour and activities explicitly. Ultimately, direct observation and testing with the intended exceptional user (be they a disabled human or animal), during all stages of development is particularly important, as they provide specialized and invaluable direction, guidance, experience and insight that cannot be accessed in any other way. This is especially true when we consider the design of species-appropriate ACI relative to the enormous diversity of animal species whose motivational, cognitive and emotional states must be inferred from species specific external behaviour (Ritvo & Allison, 2014). Ultimately, the designer will only be able to a) design appropriate exceptional-user systems and b) assess the efficacy of his design, if exceptional users are involved in both development and analysis.

6.2. Potential benefits to universal HCI

For years medical science has examined extreme cases (i.e., significant dysfunction) to further our understanding of the human body and mind. Such examination has provided useful information on human anatomy and cognition. This paradigm can also be employed in HCI research. Exceptional users push the boundaries of technology and compel innovation. Furthermore, accessible designs can, in some cases, increase function and decrease costs for all users (Vanderheiden, 1990). Whereas abled bodied human users are likely to perform sufficiently despite suboptimal technology, disabled or animal users are less likely able to do so. Consequently, these exceptional users can be employed to detect deficient interface design that able-bodied humans would tolerate. Furthermore, disabled human users and animal users provide a challenge for interface development that can stimulate the design of new and improved interfaces (Bergman & Johnson, 1995, pp. 87–114; Newell, 1993). History suggests that consideration of exceptional users (i.e., animals and disabled humans) can catalyze exceptional design (Edwards, 1995). Several innovative HCI interfaces have been inspired and facilitated by rehabilitation research. For example, the design of the foot-operated mouse (Pearson & Weiser, 1986) was predated by foot-operated systems for physically disabled individuals, and the auto completion system for text (Jakobsson, 1986) was predated by many similar systems designed for cognitively- and/or physically- disabled individuals. On a broader scale, Alexander Graham Bell, before he invented the first telephone, began his research to investigate methods of assisting the deaf (Edwards, 1995; Gray, 2010). In the same vein, tape recorders were designed to provide audio books for the blind (Newell, 1993). Other products originally designed in response to the needs of disabled individuals include closed captioning, the typewriter, predictive text, and the TV remote control (Darzentas & Miesenberger, 2005; Edwards, 1995; Helal, Mokhtari, & Abdulrazak, 2008; Tumlin & Heller, 2004). For this very reason, at CHI 2001, Vanderheiden (cited in Resner, 2001) encouraged interface designers to consider disabled users even when they were designing for a mainstream audience. By considering an exceptional target user, the designer can intentionally or unintentionally benefit a wider audience (Resner, 2001).

7. Conclusion

HCI interface and design, and the inherent benefits to its users can be extended to animals through ACI. ACI has the potential to provide animal environmental enrichment, exercise, entertainment, distraction and comfort and to enhance human-animal relations. To design species-appropriate ACI interfaces, the designer should acquire an intimate knowledge of the target-species and their environment that goes beyond general facts and conventions. Thus, empirical study of, firsthand encounters with, and direct usability testing of, the user-species in their natural contexts is crucial. It is essential to include the target-species in ACI design from the beginning to completion. As Wirman (2013, p. 1213) emphasizes, what may appear like unusual behaviour in the animal's interaction with the ACI system can aid designers' understanding of their implicit design decisions. For example, Cheok et al.'s (2011) observation of counter-intuitive animal behaviour led them to reassess their assumptions of hamster motivation, thereby contributing to a successful design. Part of the ACI designer's role then, is a) to study the user species' natural behavioural patterns, means of communication and activities in the animal's context and b) to design systems that mimic, support and augment these natural species-specific tendencies.

While we have examined ACI in the context of user-centered design, it is important to acknowledge that alternative HCI paradigms may also prove fruitful. For example, the ecological approach to HCI (Bennett & Flach, 2011) and aspects of ecological interface design (EID) hold promise. While EID is usually applied to complex interfaces (Vicente, 2002), some aspects of the paradigm are potentially applicable to ACI as well. EID emphasizes separate and focused analysis of the 'work domain'. When applied to ACI, this would involve analysis of the animal's environment including the embedded system and its affordances. A claimed advantage of EID is that this focus on ecological context, rather than task, provides robustness to unintended or unforeseen use scenarios. Because the ACI designer can less readily (a) discern users' goals or tasks and (b) predict how users will approach or interact with the system, a focus on ecological context could prove particularly advantageous in ACI. Finally, emphasis on lower levels of the 'skills, rules and knowledge taxonomy' used in the ecological approach (Rasmussen, 1983) (i.e., direct action on the interface) as a means of reducing cognitive effort is even more important for animals than humans. Animal users often cannot appreciate abstract models of the system and may have difficulty learning arbitrary rules; however, they can be expected to act directly on the system if it conforms to their natural modes of action.

Like HCI for the disabled, ACI is directly relevant and beneficial to HCI. The alternative approaches and innovation necessary for ACI have the potential to guide future HCI design and innovation for humans as well. The development of ACI systems for animals with atypical cognitive ability and physiology may be applicable to certain human user groups (e.g., the young, old or cognitively impaired). Consider for example, how the study of optimal interface design for primates might aid in improving interface design for preverbal or cognitively impaired children or how Rover@Home might be useful in teaching preverbal children the names, colours and shapes of objects they encounter as they explore their environment (Mancini, 2013). Finally, by improving methods to minimize bias in modeling and assessment, and by introducing novel methods of animal user experience assessment, HCI modeling and assessment serves to benefit as well.

There will likely be unpredictable potential benefits of ACI research and design for nonhumans and humans alike. Far from being only a superficial, fleeting sub discipline of HCI, ACI has a large user base and implicit promise. With the ever-increasing quantity, affordability and accessibility of sophisticated remote and mobile computer technologies, there has never been a more fertile time for ACI innovation.

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