JZAR JOURNAL OF ZOO AND AQUARIUM RESEARCH
www.jzar.org

Research article

JZAR Research article

Implementing portable touchscreen setups to enhance cognitive research and enrich zoo-housed animals

Vanessa Schmitt[1,2]

[1]Tiergarten Heidelberg gGmbH, Heidelberg, Germany; [2]Centre for Organismal Studies (COS), University of Heidelberg, Heidelberg, Germany

Corresponding author: V Schmitt, vanessa.schmitt@cos.uni-heidelberg.de

Keywords: Touchscreen technology; comparative cognition, animal-computer interaction; welfare; primates; birds; enrichment; social group

Article history:
Received: 10 Aug 2017
Accepted: 19 Mar 2019
Published online: 30 Apr 2019

Abstract

To understand the evolutionary development of cognition, comparing the cognitive capacities of different animal species is essential. However, getting access to various species with sufficiently large sample sizes can be very challenging. Zoos, housing large ranges of animal taxa, would offer ideal research environments, but zoo-based studies on cognition are still rare. The use of touchscreen computers to explore the cognitive abilities of nonhuman animals has been shown to be highly applicable, and simultaneously offers new enrichment possibilities for captive animals. To facilitate zoo-based research, the assembly and usage of newly developed touchscreen computer systems (Zoo-based Animal-Computer Interaction System, ZACI) are illustrated, which can be used in various zoo environments, and importantly, with different taxa (e.g. primates, birds). The developed setups are portable, can be attached to various mesh sizes, and do not need any external power supply while being used. To evaluate the usability of the ZACI, they were tested with experimentally naïve subjects of three great ape species (orang-utans, chimpanzees, gorillas) housed at Zoo Heidelberg, Germany, demonstrating ZACI to be animal-proof, easy to handle, and of great interest to the animals. Animals could be tested within their social group, as each subject had access to its own device during testing. To support the implementation of touchscreen setups at other facilities, the training procedure is also illustrated and first data on the apes' performance in a simple object discrimination task are presented. Portable touchscreen setups offer the great possibility to enhance collaboration between zoos and researchers, allow a standardisation of methods, and improve data collection.

Introduction

Comparing the cognitive abilities of different animal species to elucidate the evolutionary trajectories of cognitive development constitutes a promising research avenue (Herrmann et al. 2007; Schmitt et al. 2012; Benson-Amran et al. 2016; Vonk 2016; Whiten 2017), but often studies struggle with limited access to various species or subjects (MacLean et al. 2012; Tomasello and Call 2011; Thornton and Lukas 2012). Zoos, housing large ranges of animal taxa, offer ideal research environments, but although cognitive research is increasingly taking place in zoos in recent years, especially in the USA, it is still conducted at only a few facilities in Europe (Hopper 2017). Some zoos do not support basic scientific research; others do not have financial resources to hire scientific personal; and often logistical limitations prevent scientific research in zoos (see Hopper 2017 for a review).

Computerized technology provides well-established tools to conduct cognitive experiments with captive animals (e.g. Savage-Rumbaugh et al. 1986; Matsuzawa 1985; Bielick and Doering 1997; see also Leighty and Fragaszy 2003) and there is even a new research field emerging focussing on Animal-Computer Interactions (ACI) (Pons et al. 2015; Mancini et al. 2017). In recent years, Lincoln Park Zoo in Chicago, USA, already established a comparative touchscreen research program with gorillas (*Gorilla gorilla gorilla*), chimpanzees (*Pan troglodytes*) and macaques (*Macaca fuscata*) (Egelkamp et al. 2016). In addition to primates, touchscreen experiments are now also being conducted with a large range of different animal species and taxa, for example, birds (*Nestor notabilis*, O'Hara et al. 2015), bears (*Ursus americanus*, Vonk and Beran 2012; *Helarctos malayanus*, Perdue 2016), dogs (*Canis lupus familiaries*, e.g. Zeagler et al. 2016) and even tortoises (*Chelonoidis carbonaria*, Mueller-Paul et al. 2014).

Touchscreen technology offers a powerful research tool for various reasons. First, touchscreen computers enable a valuable increase in accuracy and clarity of data collection, especially in comparison to manual tasks (e.g. Benson-Amram et al. 2016). Touchscreens facilitate very fine-grained measurements and accurate recordings of metrics like latency, improving cross-species comparisons (e.g. chimpanzees and humans, Inoue and Matsuzawa 2007). Second, data collection increases considerably, as it is possible to run hundreds of standardised and replicable trials in very short time spans (e.g. Fagot and Paleressompoulle 2009). Third, the variety of cognitive research questions that can be explored is nearly unlimited, and range from, for example, object, quantity or facial discrimination experiments (e.g. Vonk and Beran 2012; Micheletta et al. 2015; Johnson-Ulrich et al. 2016), examining the understanding of social interactions (e.g. Waller et al. 2016), evaluating emotional effects on cognition (e.g. Allritz et al. 2016), to virtually simulated reality experiments (Dolins et al. 2014; 2017). Fourth, when set up as automated systems, they do not need constant interaction with a human experimenter, preventing unintentional biases such as cueing subjects' responses, which, in turn, leads to more robust results (Clever Hans effect, e.g. Schmidjell et al. 2012). This minimal human interaction also facilitates the implementation of such test devices in zoological settings, where access to animals and research personnel may be limited. When using multiple touchscreen setups it is even possible to test animals individually, but within their social group (Gazes et al. 2013; Fagot and Paleressompoulle 2009), and the influence of animals working in parallel to each other can be tested (e.g. Martin et al. 2011; Schmitt et al. 2016).

Besides increasing the number of potential test subjects and improving data collection for cognitive research, conducting touchscreen studies at zoos may also contribute to enhancing animal welfare (e.g. Perdue et al. 2012a). A recent study in zoo-housed crested macaques (*Macaca nigra*) indicated that conducting scientific studies using touchscreens positively influenced their wellbeing (Whitehouse et al. 2013), and so-called 'cognitive enrichment' is now being considered as an important factor in zoo welfare management (see Clark 2011 and 2017 for review). Interestingly, some zoos and sanctuaries already give their orang-utans access to iPads as behavioural enrichment activity (Boostrom 2013, Wirman 2013).

Touchscreen technology is thus increasingly applied to test the cognitive abilities of, or to enrich, zoo-housed animals, but the actual setups used vary. Some studies use built-in systems (e.g. Ross 2009; Micheletta et al. 2015; Allritz et al. 2016), which often need expensive or laborious construction work that some zoos do not support. Furthermore, most of the time, these built-in touchscreens are only accessible or used by a limited number of subjects or species per zoo (e.g. Perdue et al. 2012a; Micheletta et al. 2015). In contrast, portable or at least moveable touchscreen systems can allow for a variety of species tested within the same zoo. Some studies place a single tablet or touch-monitor in front of the animals, but these setups often require close human contact, such as holding the monitor in front of the subjects (e.g. Vonk 2003; Wirman 2013) or feeding the animals manually (e.g. Sonnweber et al. 2015; Altschul et al. 2017); procedures which some zoos do not approve. Therefore, at Zoo Atlanta, USA, researchers use stand-alone, portable touchscreen setups that can be attached to the mesh of the animals' enclosures and are equipped with food dispensers (Diamond et al. 2016; Perdue 2016). At Indianapolis Zoo, USA, C.F. Martin is also developing similar portable touchscreen setups to work with great apes with improved technological components, such as attaching a battery to allow a cordless usage (C.F. Martin, *personal communication*, June 2017). Detailed documentation on the construction of such touchscreen setups, however, are not often published, are only available for systems designed for laboratory purposes (e.g. Steurer et al. 2012, Calapai et al. 2016; see also http://lafayetteneuroscience.com/ for a primate-specific setup available for purchase), or describe built-in setups like the arena system (Martin et al. 2014), which are not easily implemented at most zoos.

To facilitate cognitive testing with zoo-housed animals, the assembly and usage of a newly developed portable touchscreen setup is illustrated, one which can be used in various zoo environments (e.g. different mesh constructions) and, importantly, with different animal species (also non-primate). The setups are portable, can be attached to various mesh sizes, and do not need any external power supply while being used. To validate the usability of the touchscreen setups, they have been tested with orang-utans (*Pongo abelii*), chimpanzees (*Pan troglodytes*) and gorillas (*Gorilla gorilla gorilla*) at Zoo Heidelberg (12 individuals, ages ranging from 5 to 45 years). The aim of the study is twofold. First, to illustrate the assembly of the setup to facilitate collaborations between researchers and zoos, and to enable a possible reproduction at other facilities. Second, to examine whether and how experimentally naïve subjects of three different great ape species interact with the new touchscreen setups, and to suggest how they can be introduced to use such devices.

Material and methods

The Zoo-based Animal-Computer Interaction system (ZACI)

The development of the Zoo-based Animal-Computer Interaction System (ZACI) was inspired by the portable touchscreen setups used at Zoo Atlanta (*personal observations* and *personal communication* by R. Paxton Gazes, June 2014) and Indianapolis Zoo (C. F. Martin, *personal communication*, July 2014 and March 2015), but integrates different technologies and newly developed design components, such as the Electronic Control Unit (ECU, see below). The ZACI functions as a stand-alone, portable system,

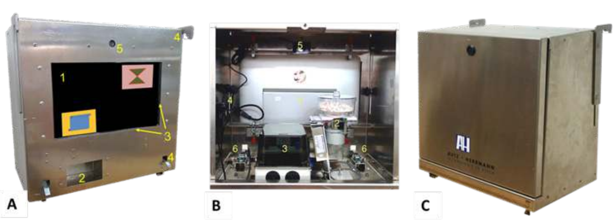

Figure 1: A) Front view of the touchscreen system including a 15.6" laptop, which is located behind a 10 mm Plexiglas® panel (1), an opening for reward pellets (2), a 15.6" infrared touchframe surrounding the screen (3), hooks adjustable to different mesh sizes (4), and a webcam to film the subjects (5). B) Back view of the touchscreen system showing laptop (1), food dispenser (2), the self-developed ECU with power supply (3), a USB-hub to connect the components (4), the webcam (5), and hooks (6). C) Back view of the setup with attached back cover.

which can be attached to the outside iron bars of the animal's enclosure. It is adjustable to different mesh sizes via adjusting joined hooks at the top and at the bottom of the apparatus (Figure 1 and supplemental information). Furthermore, it does not need any external power supply while being used, reducing the risk of electricity cables within an animal's proximity.

The core of a unit is a 15.6" convertible laptop (HP ENVY x2 15-c000ng 2in1, by HP® Inc., Palo Alto, CA) running Microsoft Windows®, which can be used as a tablet computer with a detachable keyboard (Figure 1a and 1b). However, any convertible laptop or tablet computer of this size could be used to run the ZACI. The laptop slides in and out of the system in seconds to be recharged or programmed, using hooks attached to the aluminium casing. The detachable keyboard functions via Bluetooth and allows operating the laptop even when attached to the system. To protect the laptop from damage and dirt, a transparent Plexiglas® panel (width 10 mm) is located directly in front of the screen and adjusted to the metal casing, so that the animals only touch the Plexiglas panel and not the laptop. To register touches a 15.6" infrared (IR) touchframe (Model PPMT-IR-0156GR-WP, by KEYTEC®, Inc., Garland, TX) surrounds the Plexiglas panel, facing the subjects, and is connected to the laptop via USB. The IR touchframe technology allows the device to be operated not only by the touch of a finger, but also by a bird's beak, a tongue or a stick. In fact, anything penetrating the infrared barrier can be used to elicit a response of the touchscreen (Steurer et al. 2012). For rewarding correct trials, the unit contains a pellet dispenser (Model ENV-203-190IR, by Med Associates Inc., St. Albans, VT), which ejects standardised reward pellets (190 mg, manufactured by TestDiet®, St. Louis, MO) in different flavours (e.g. fruit punch, apple, banana, peanut butter) (Figure 1b). However, other pellet dispensers and reward pellets could be integrated into the system depending on the species being tested. The laptop and the food dispenser are coupled via a self-developed ECU, containing the necessary electronics and a rechargeable battery (see supplemental information). Furthermore, each ZACI includes an additional webcam (Live! Cam Sync HD 720p, by Creative®, Dublin, Ireland), making it possible to film the animals while working on the screen. The laptop, IR touchframe, ECU and webcam are interconnected via an additional USB-hub (USB 3.1 Hub, by CSL-Computer GmbH & Co. KG, Hannover, Germany) with four interfaces attached to the inside of the metal casing.

All components of the ZACI are integrated in an aluminium casing (45 cm x 50 cm x 26 cm, H x W x D) manufactured by a local company (Autz & Herrmann GmbH, Heidelberg, see supplement for more pictures on the assembly of the ZACI). Aluminium is much lighter than steel (a 100 mm x 100 mm x 5 mm board made of steel weighs 0.39 kg, made of aluminium only 0.14 kg), but offers the same stability and cleanliness. The ZACI, equipped with all components, weighs approximately 12 kg, which is approximately half the weight of the Monkey CANTAB system sold by Lafayette Instrument®, and the portable touchscreen setups used at Zoo Atlanta. An optional back cover protects the interior of the ZACI from liquids like water or urine and unwanted access (Figure 1c). The detailed construction plans of the aluminium casing are property of the company Autz & Herrmann GmbH, but further details and measurements can be made available on request (www.autz-herrmann.de). Furthermore, the company can easily produce the aluminium casing on request. All components of the ZACI have been manufactured to ensure that the tested individuals cannot dismantle the setups or hurt themselves. As the mesh of animal enclosures in European zoos often allows primate subjects to reach through with their arms, the metal casing is constructed as a smooth rectangular box, so the animals cannot hold onto and pull at parts of the setup when attached to the mesh. There are no loose parts in the proximity of the subjects. Furthermore, attaching the setup to the mesh can be performed with the arms of the experimenter located inside the metal casing (with the back cover removed), protecting the human from animals' reach.

While the animals work at the units, the setups can be remotely controlled via Wi-Fi using an additional tablet computer (e.g. Microsoft Surface 3) to launch and control the experiments. The animal laptop and control tablet were coupled using the software TightVNC (http://www.tightvnc.com/). As Wi-Fi is not common in most animal holding areas, we created a private Wi-Fi using a mobile router (Mobile WLAN router M7350 by TP-link Technologies Co., Ltd, Germany).

To programme and run experimental procedures, a custom-made software was developed using the freely available programming language JavaTM (Oracle®). The software records the identity of the individual (manual input), the type of the stimuli used in the task, the area each stimuli was presented on at the screen, the reaction time of the subject (i.e. the latency to complete a trial), whether the response was correct or not, the exact point (with x and y coordinates) where the animal touched the screen, etc. The settings of each experiment can be easily adjusted via small property files (see https://en.wikipedia.org/wiki/.properties). Java is very independent of the operating system and hardware. Thus, the present experiments can run on Microsoft Windows®, Linux® and Apple macOS®. Furthermore, other behavioural software (e.g. E-Prime®) could be used to run the ZACI. The only part of the newly developed software, which is crucial to control the pellet dispenser, is the low-level component controlling the USB relay card included in the self-developed ECU. This software code could also be integrated into other behavioural software and can be accessed from the supplemental material.

Table 1: Name, species, sex and age at testing of the subjects participating in the study.

Subjects	Species	Sex	Age at testing
Ujian	Orang-utan	M	21
Puan	Orang-utan	F	26
Sari	Orang-utan	F	12
Heidi	Chimpanzee	F	[1]approx. 45
Susi	Chimpanzee	F	[1]approx. 44
Lulu	Chimpanzee	F	42
Conny	Chimpanzee	F	[1]approx. 42
Bobo	Gorilla	M	24
Kwame	Gorilla	M	5
ZsaZsa	Gorilla	F	29
N'Gambe	Gorilla	F	15
Shaila	Gorilla	F	9

[1]Subjects were wild-born and their age had been estimated

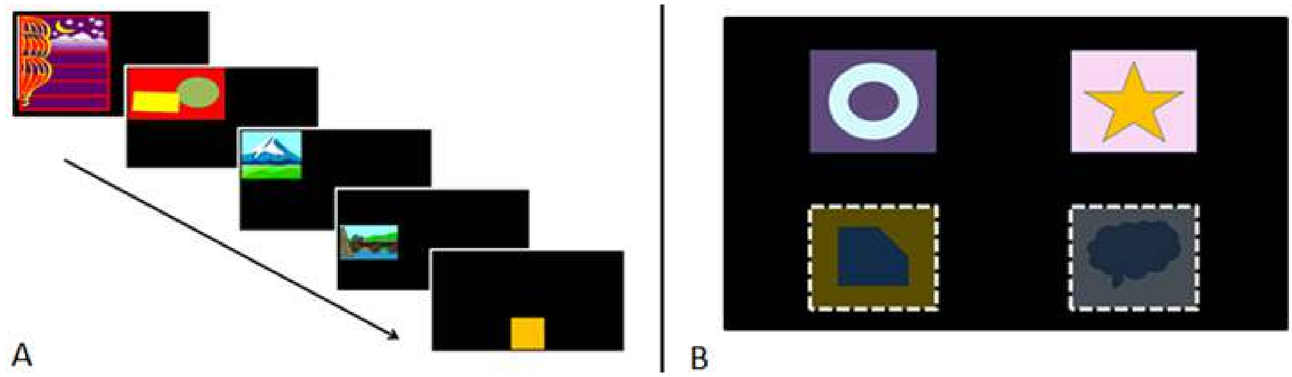

Figure 2: A) Representation of the successive stages of the Shaping experiment. The pictures the animals had to touch became smaller and ultimately preceded by a start signal (yellow square). B) Possible screen locations and picture samples of the Object Discrimination task. On each trial two pictures randomly appeared at the top, the bottom, only at the left or right side of the screen, or diagonally.

Subjects

Five gorillas (*Gorilla gorilla gorilla*), four chimpanzees (*Pan troglodytes*) and three orang-utans (*Pongo abelii*), were included in the study (Table 1) and were tested between August 2015 and June 2016 (the gorillas resumed training in June 2017). All species were living within their respective social groups housed at Zoo Heidelberg, Germany, and had access to indoor and outdoor exhibits. None of the subjects had ever participated in any touchscreen experiments before. The animals were not food or water deprived for testing. All testing was non-invasive and subjects participated voluntarily. All experiments followed the Guidelines for the Treatment of Animals in Behavioural Research and Teaching published by the Association for the Study of Animal Behaviour (http://asab.nottingham.ac.uk/downloads/guidelines2006.pdf).

General Procedure

The orang-utans and chimpanzees were tested within their social groups and were not separated for the touchscreen tasks. The gorillas, however, were usually separated in the indoor areas of their exhibit for afternoon feeding and cleaning, irrespective of the touchscreen testing (except for Kwame, the youngest subject, who always stayed with one of the females). Due to husbandry reasons, we began testing the gorillas during this time period, but after a couple of months they were also tested without being separated. As five units of the ZACI had already been built, it was possible to set up one unit for each subject. Each unit was attached to the outside of the iron bars of the animals' indoor exhibits for approximately 45 min per day, approximately three to five times a week depending on the least interference with regular husbandry procedures. At their first encounter with the touchscreens, we allowed the animals tested in groups to go to any unit. As soon as they had learned that touching the screens resulted in rewards, however, we trained the subjects that only one specific device would work for each animal. When Subject A tried to activate Subject B's touchscreen, we unplugged the USB of the IR-screen. Thereby the animals learned within a couple of days which device they could work on. This procedure ensured reliable data collection in the following cognitive experiments.

Experimental Procedure

Shaping

The initial experiment of the study trained the subjects to use the touchscreen and shaped their touching movements to reliably select small pictures on the screen. It consisted of six stages, guiding the animals from touching the whole screen to touching small pictures on the screen (Figure 2a and Table 2). In each stage, a random picture (clipart, geometrical forms or photograph) was presented at the screen. In Stage 1, touching any part of the screen, that is, either the picture or the background area, resulted in a positive feedback: an immediate auditory feedback ("ping", 865 msec), a green screen (1 sec), and a reward pellet. In all

Table 2: Specifications for each stage of the Shaping procedure, that is, the area the subjects had to touch, the size of the presented pictures, and the criteria to pass each stage.

Stage	Required touch at	Picture Size (W x H; cm)	Criterion to pass each stage	
			Number of Trials	Time per Trial
1	Whole screen	17 x 19.4	12	6 sec (8 sec for gorillas)
2	Picture	17 x 19.4	20	6 sec
3	Picture	17 x 10	20	6 sec
4	Picture	10.5 x 10	20	6 sec
5	Picture	10.5 x 6	20	6 sec
6	Start Signal + Picture	10.5 x 6	20	6 sec
			+ 10 trials	3 sec

Table 3. Number of trials and total number of testing days each subject needed to pass the six stages of Shaping. Numbers written in italics mean that the difficulty was manually increased to facilitate training.

	Orang-utans			Chimpanzees				Gorillas				
Stage	Ujian	Puan	Sari	Susi	Conny	Heidi	Lulu	Bobo	Kwame	Shaila	ZsaZsa	N'Gambe
1	62	111	48	80	56	43	155	*503*	*483*	*550*	113	204
2	45	145	156	391	124	*357*	*352*	*474*	*433*	*350*	134	293
3	33	*80*	192	92	138	*413*	*95*	*472*	*350*	*350*	289	337
4	*50*	47	38	107	37	*165*	*190*	89[1]	*350*	*305*	*250*	266
5	*50*	*40*	20	369	261	*93*	*293*		101	190	215	26[1]
6	37	69	32	128	30	128	52		39	30	80	
Total Days	5	7	7	5	4	10	15	23[2]	12	11	6	19[2]

[1]Stage not finished yet; [2]Maximum number of testing days so far

subsequent stages, touching the black background area instead of a picture did not elicit any feedback. Instead, only touching the presented picture was rewarded. In Stage 6, a yellow square (representing a start signal) preceded each picture. The subjects had to touch the square and the following picture to receive a reward. In each stage, the position of the pictures on the screen was pseudorandomised (covering each part of the screen equally) and varied from trial to trial.

The experiment was designed to train each animal in a self-paced manner, so no predetermined number of trials in each stage was applied. Instead, each subject proceeded to the next stage after reaching a specific criterion, which demonstrated that the subject was able to focus on and work at the touchscreen for a certain amount of time (Table 2). For example, to pass Stage 1, the subject had to touch the screen for 12 consecutive trials needing not more than 6 seconds to complete each trial (the gorillas were allowed to take 8 seconds per trial as they needed more time to take the reward pellets out of the opening than the chimpanzees and orang-utans). In Stages 1 to 5, these reaction times were measured as the latency from the onset of each new picture on the screen until the subject touched the picture. From Stage 6 on, however, reaction time referred to the latency from touching the yellow start signal until touching the pursuing picture. In addition to their reaction time, the software also recorded the position of each touch at the screen, that is, also at the unrewarded black background area, to examine the touching behaviour.

Object Discrimination

After the animals had successfully mastered the Shaping procedure they moved on to their first Object Discrimination task. In this experiment the subjects learned to discriminate between two pictures (S+ and S-). Touching S+ resulted in the already known auditory feedback ("ping"), a green screen (1 sec), and a reward pellet. Touching S- resulted in a new negative auditory feedback ("buzz", 300 msec), a black time-out screen (3 sec) and no reward pellet. Each trial began with the start signal (yellow square). All subjects received the same picture pairs (i.e. random geometrical forms), but whether a picture was assigned correct (S+) or incorrect (S-) was pseudorandomised. The pictures where randomly presented at four possible screen locations to prevent the development of any side biases (Figure 2b). After reaching a success ratio of 90% within 12 trials, that is, 11 out of 12 trials correct, a new pair of symbols appeared on the screen and the subject entered the next level. The probability to choose 11 out of 12 trials correct by chance is P=0.003. The correct and incorrect pictures did not share any specific features between the levels. Data for the first three picture pairs the subjects successfully discriminated are presented.

Results

Usability of the ZACI

The newly developed portable touchscreen systems proved to be highly applicable for use with great apes housed at Zoo Heidelberg. Even after several months of testing, the animals were

Figure 3: Orang-utan Sari working at the Zoo-based Animal-Computer Interaction system (ZACI). The system is attached to the outside bars of the animals' enclosure and the subjects touch the screen through the mesh (Photo credit: Heidrun Knigge, Zoo Heidelberg).

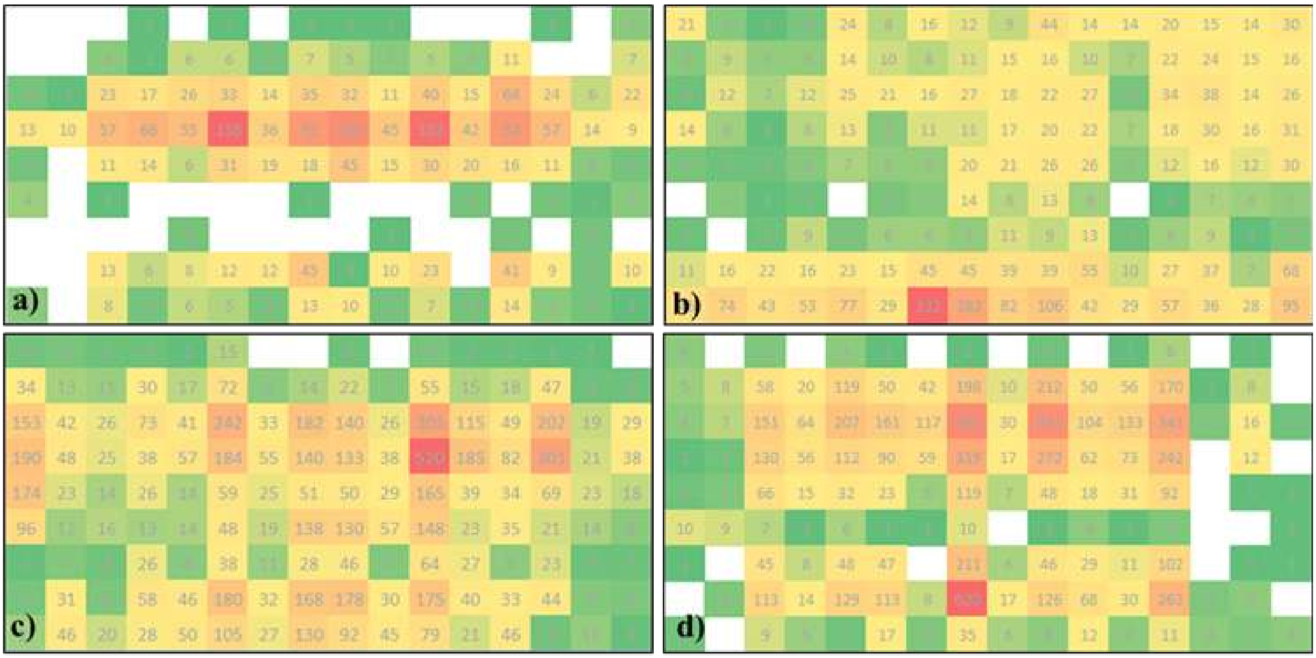

Figure 4: Distribution of touches on the screen during the Shaping task. The colour code indicates increased number of touches with increasing redness (heat map). The grey numbers give the total amount of touches at each square based on a 16 x 9 grid. a) orang-utan Sari, b) orang-utan Puan, c) gorilla Kwame, d) chimpanzee Conny.

not able to dismantle or destroy any parts of the setups. Each subject interacted with the new apparatus and most learned how to control the touchscreen through the mesh of their enclosures (Figure 3, and Video S1).

Shaping

After 2 months of training for each species, 10 out of the 12 apes tested had passed the Shaping procedure. In fact, all orang-utans, all chimpanzees and three gorillas had learned within 4 to 15 testing days to reliably touch small pictures on the screen (Table 3). The other two gorillas still have to learn how to consistently touch small pictures, but all subjects showed large interest in the touchscreen systems and participated regularly in the experiments.

Initially, each subject should move to the next stage of Shaping after reaching a specific criterion, that is, passing a predetermined number of trials within a given timespan. However, during training some subjects had trouble meeting this criterion, as they either needed more time to take and eat the reward pellets or were generally more distracted. When a subject reliably touched the picture on the screen and only this timing issue interfered with advancement, difficulty was manually increased, for example, picture sizes were decreased. This method enhanced efficiency of training for all subjects, except Bobo, the silverback gorilla, who stopped participating when difficulty was manually increased. Only decreasing difficulty again, and then increasing it after 50 trials, got him back to work at the touchscreen. Note, however, that manually increasing task difficulty was only applied until Stage 5. In Stage 6, each subject had to fulfil criterion, that is, demonstrating a reaction time of less than 6 seconds for 20 consecutive trials and an additional 10 trials with less than 3 seconds per trial, for the Shaping procedure to be passed.

The computer also recorded where the animals touched the screen, that is, whether and where they touched the unrewarded black background area. Although touching the background had no consequences for the subjects, it gave valuable information about any side preferences of the subjects' touches. Sari's heat map showed, for example, that she had difficulties touching the part of the screen below the horizontal bar of the enclosure (see Figure 4a). This behaviour explained the large number of trials she needed to pass Stage 3, where the pictures only covered a quarter of the screen. After putting some honey on the lower part of the touchscreen, she quickly expanded her touches and finished Stages 4 to 6 needing the least number of trials of all subjects. In general, however, the bars in front of the touchscreen caused no

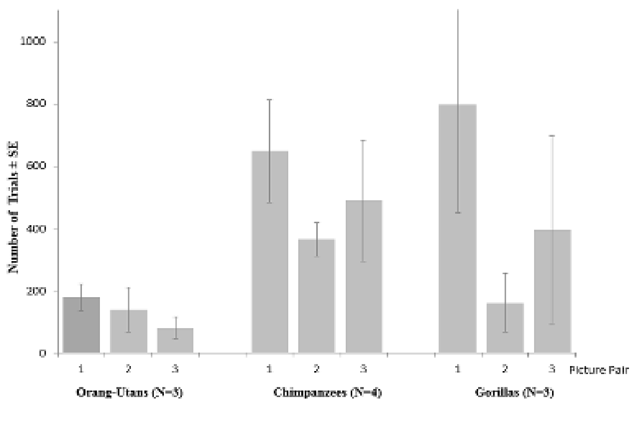

Figure 5: Mean number of trials ± standard error (SE) the apes needed to discriminate the first three random picture pairs in the Object Discrimination experiment.

Table 4: Number of incorrect, correct and total trials each subject needed to pass the three Object Discrimination tasks.

Species	Subject	Picture Pair	Incorrect	Correct	Total trials
Orang-utan	Ujian	1	46	63	109
		2	63	53	116
		3	24	32	56
	Puan	1	62	108	170
		2	7	22	29
		3	7	29	36
	Sari	1	107	150	257
		2	132	139	271
		3	66	85	151
Chimpanzee	Conny	1	289	338	627
		2	204	216	420
		3	453	563	1016
	Susi	1	539	546	1085
		2	185	108	293
		3	191	202	393
	Heidi	1	301	296	597
		2	220	269	489
		3	36	47	83
	Lulu	1	126	161	287
		2	134	124	258
		3	241	224	465
Gorilla	ZsaZsa	1	689	794	1483
		2	157	193	350
		3	530	464	994
	Kwame	1	265	293	558
		2	14	36	50
		3	24	36	60
	Shaila	1	173	181	354
		2	37	49	86
		3	49	83	132

difficulties for the subjects. All other subjects quickly learned to touch all parts of the screen (see Figure 4b-d for further examples).

Object Discrimination

After the subjects had successfully passed the Shaping procedure, they proceeded to their first Object Discrimination experiment, that is, three orang-utans, four chimpanzees and three gorillas participated. In this experimental paradigm, all subjects experienced a negative feedback: a buzz sound, no reward and a time-out, for the first time. However, all subjects continued to participate in the experiments and successfully discriminated three random picture pairs. Although visual inspection of Figure 5 suggests that orang-utans performed slightly better than chimpanzees and gorillas, the results showed no significant species differences (two-way repeated measure ANOVA with species and Picture Pair as fixed factors and number of total trials as dependent variable, $P=0.209$), but a significant effect of Picture Pair ($P=0.030$), with subjects performing significantly better with Picture Pair 2 compared to Picture Pair 1 ($P=0.027$). Instead, large individual differences have been observed, for example, gorilla Kwame performing equally well as orang-utan Puan in discriminating Picture Pairs 2 and 3 (Table 4). As four possible screen locations were used, the development of any side biases was not observed.

Dicussion

The newly developed Zoo-based Animal-Computer Interaction System (ZACI) proved to be highly applicable for work with zoo-housed primates. All subjects interacted with the touchscreen systems on a regular basis and 10 out of 12 great apes learned to reliably use the setups within 4 to 15 days of testing. The other two gorillas also showed large interest in the setups but need some additional testing days to finish the Shaping procedure. Using the whole area of the touchscreen through the mesh of their enclosure caused only some difficulties for one subject but could easily be solved by putting honey on the screen. Placing the touchscreen on the outside of the mesh is also done at Zoo Atlanta and Marwell Zoo (Diamond et al. 2016; Perdue 2016; Micheletta et al. 2015), demonstrating a satisfactory touchscreen usability. Furthermore, even after several months of testing, the apes were not able to dismantle or destroy any of the setups. Given the strength and intelligence of great apes, this confirms that the developed setups should also be safe to use with other animal species. The usage of an infrared touchframe allows the setup to be used also with non-primate species. A variety of studies already demonstrated that an infrared technology allows touchscreen usage by various animal species and taxa as for example birds, bears, dogs and tortoises (e.g. Steurer et al. 2012; Vonk and Beran 2012; Mueller-Paul et al. 2014; Perdue 2016; Zeagler et al. 2016). The ZACI could therefore easily be introduced to a variety of animal species, also outside of a zoo setting. As the system can be closed with an optional back cover, protecting the interior from dirt and spray water, and does not need any power supply while being used, it could furthermore also be used outdoors, enabling an application at sanctuaries for example (e.g. Wirman 2013).

The training method applied in the Shaping task showed to be adequate for most subjects and elicited interest to continue touching the screen. Some subjects were not able to reach the predetermined temporal criterion in some Stages due to their slower touching frequencies, but manually increasing task difficulty considerably facilitated training. Only Bobo, the silverback gorilla, stopped working after manually increasing difficulty, and only participated again after resetting the stage. Therefore, a slightly modified version of the training procedure might be more appropriate. Niessing and colleagues (2015) developed an automated training algorithm that uses a staircase procedure to train rhesus macaques (*Macaca mulatta*) the required touch at the screen. Their software either increases or decreases task difficulty based on the subject's performance within the last 50 trials. Implementing a similar procedure might help to train animals without any human interference necessary and maybe even faster than has been accomplished in this study.

The quick acquisition of reliable touches by the animals now enables the collection of large datasets on their cognitive capacities. The first Object Discrimination experiment already demonstrates the usability of the setups to conduct experiments on comparative cognition. All subjects successfully discriminated three random picture pairs within only seven days of testing. The possible problem of developing side biases (see e.g. Allritz et al. 2016) could be solved by presenting the pictures not only at two, but at four possible locations, with the pictures also appearing either at only the left or right side of the screen, or diagonally. Interestingly, in our Object Discrimination experiment the orang-utans performed slightly better than chimpanzees and gorillas. To declare any true species differences, however, larger sample sizes would be desirable. Establishing portable touchscreen systems at other zoos with a greater collaboration between researchers could thus enhance data collection and enable robust analyses, helping to significantly advance the field of comparative cognition (see also Thornton and Lukas 2011).

In addition to increasing the number of potential test subjects for cognitive research, the usage of digital technology can serve as enrichment and even enhance the welfare of captive animals (Yamanashi and Hayashi 2011; Fagot et al. 2014; Bennett et al. 2016). The experimentally naïve apes of Zoo Heidelberg all interacted with the setups on a regular basis and some subjects even worked at the ZACI for 45 min in each session, demonstrating the subjects' interest in the touchscreens and suggesting their enriching value. A new project at Zoo Melbourne created digital projections for their orang-utans, allowing the apes and visitors to play interactive games (Webber et al. 2017). As a positive side effect, studies have shown that zoo visitors engaging with such technology show greater knowledge and interest in conservation issues, which could ultimately help to protect endangered species (e.g. Perdue et al. 2012b; Whitehouse et al. 2014).

In conclusion, portable touchscreen setups offer the possibility to significantly enhance data collection for scientific research on zoo-housed animals. In addition, they can improve animal welfare as they provide valuable enrichment to captive animals.

Acknowledgements

Special thanks go to Christian Deutsch for developing the software used to program the experimental procedures and to integrate the technical components of the ZACI, and for helping to develop the electronic control unit. Many thanks also to Regina Paxton Gazes and Christopher Flynn Martin for sharing their knowledge on portable touchscreen devices and many helpful discussions during the construction. I am also grateful to student researchers, Marith Booijen, Jamie Dau and Sarah Schilling, for their assistance with data collection. I thank the administration and employees of Zoo Heidelberg, especially Dr. Klaus Wünnemann and Sandra Reichler-Danielowski, for supporting the study and providing the necessary infrastructure. Many thanks also to the animal caretakers of Zoo Heidelberg for their help in working with the great apes. This project was funded by the Klaus Tschira Stiftung gGmbH and the Association for the Study of Animal Behaviour (ASAB).

References

Allritz M., Call J., Borkenau P. (2016) How chimpanzees (*Pan troglodytes)* perform in a modified emotional Stroop task. *Animal Cognition* 19: 435–449.

Altschul D.M., Wallace E.K., Sonnweber R., Tomonaga M., Weiss A. (2017) Chimpanzee intellect: personality, performance and motivation with touchscreen tasks. *Royal Society Open Science* 4: 170169.

Bennett A.J., Perkins C.M., Tenpas P.D., Reinebach A.L., Pierre P.J. (2016) Moving evidence into practice: Cost analysis and assessment of macaques' sustained behavioral engagement with videogames and foraging devices. *American Journal of Primatology* 78: 1250–1264.

Benson-Amram S., Dantzer B., Stricker G., Swanson E.M., Holekamp K.E. (2016) Brain size predicts problem-solving ability in mammalian carnivores. *Proceedings of the National Academy of Sciences* 113: 2532–2537.

Bielick S., Doering Z.D. (1997) An assessment of the ''think tank'' exhibition at the National Zoological Park. Report No. 97-1, Washington, DC: Smithsonian Institution.

Boostrom H. (2013) Problem-solving with orangutans (*Pongo pygmaeus* and *Pongo abelii*) and chimpanzees (*Pan troglodytes*): Using the IPAD to provide novel enrichment opportunities. Available at http : / /hdl .handle .net /1969 .1 /150918 (accessed 10 April 2017).

Calapai A., Berger M., Niessing M., Heisig K., Brockhausen R., Treue S., Gail A. (2016) A cage-based training, cognitive testing and enrichment system optimized for rhesus macaques in neuroscience research. *Behavior Research Methods* 1–11.

Clark F.E. (2011) Great ape cognition and captive care: Can cognitive challenges enhance well-being? *Applied Animal Behaviour Science* 135: 1–12.

Clark F.E. (2017) Cognitive enrichment and welfare: Current approaches and future directions. *Animal Behavior and Cognition* 4: 52–71.

Diamond R.F., Stoinski T.S., Mickelberg J.L., Basile B.M., Gazes R.P., Templer V.L., Hampton R.R. (2016) Similar stimulus features control visual classification in orangutans and rhesus monkeys. *Journal of the Experimental Analysis of Behavior* 105: 100–110.

Dolins F.L., Klimowicz C., Kelley J., Menzel C.R. (2014) Using virtual reality to investigate comparative spatial cognitive abilities in chimpanzees and humans. *American Journal of Primatology* 76: 496–513.

Dolins F.L., Schweller K., Milne S. (2017) Technology advancing the study of animal cognition: using virtual reality to present virtually simulated environments to investigate nonhuman primate spatial cognition. *Current Zoology* 63: 97–108.

Egelkamp C.L., Hopper L.M., Cronin K.A., Jacobson S.L., Ross S.R. (2016) Using touchscreens to explore the welfare and cognition of zoo-housed primates. *PeerJ* Preprints (No. e2312v1).

Fagot J., Gullstrand J., Kemp C., Defilles C., Mekaouche M. (2014) Effects of freely accessible computerized test systems on the spontaneous behaviors and stress level of Guinea baboons (*Papio papio*). American *Journal of Primatology* 76: 56–64.

Fagot J., Paleressompoulle D. (2009) Automatic testing of cognitive performance in baboons maintained in social groups. *Behavior Research Methods* 41: 396–404.

Gazes R.P., Brown E.K., Basile B.M., Hampton R.R. (2013) Automated cognitive testing of monkeys in social groups yields results comparable to individual laboratory-based testing. *Animal Cognition* 16: 445–458.

Herrmann E., Call J., Hernández-Lloreda M.V., Hare B., Tomasello M. (2007) Humans have evolved specialized skills of social cognition: The cultural intelligence hypothesis. *Science* 317: 1360–1366.

Hopper L.M. (2017) Cognitive research in zoos. *Current Opinion in Behavioral Sciences* 16: 100–110.

Inoue S., Matsuzawa T. (2007) Working memory of numerals in chimpanzees. *Current Biology* 17: R1004–R1005.

Johnson-Ulrich Z., Vonk J., Humbyrd M., Crowley M., Wojtkowski E., Yates F., Allard S. (2016) Picture object recognition in an American black bear (*Ursus americanus*). *Animal Cognition* 19: 1237–1242.

Leighty K.A., Fragaszy D.M. (2003) Primates in cyberspace: using interactive computer tasks to study perception and action in nonhuman animals. *Animal Cognition* 6: 137–139.

MacLean E., Matthews L., Hare B., Nunn C., Anderson R., Aureli F., Brannon E., et al. (2011) How does cognition evolve? Phylogenetic comparative psychology. *Animal Cognition* 15: 223–238.

Mancini C., Lawson S., Juhlin O. (2017) Animal-Computer Interaction: The emergence of a discipline. *International Journal of Human-Computer Studies* 98: 129–134.

Martin C.F., Biro D., Matsuzawa T. (2011) Chimpanzees' use of conspecific cues in matching-to-sample tasks: public information use in a fully automated testing environment. *Animal Cognition* 14: 893–902.

Martin C.F., Biro D., Matsuzawa T. (2014) The Arena System: a novel shared touch-panel apparatus for the study of chimpanzee social interaction and cognition. *Behavior Research Methods* 46: 611–618.

Matsuzawa T. (1985) Use of numbers by a chimpanzee. Nature 315: 57–59.

Micheletta J., Whitehouse J., Parr L. A., Waller B.M. (2015) Facial expression recognition in crested macaques (*Macaca nigra*). *Animal Cognition* 18: 985–990.

Mueller-Paul J., Wilkinson A., Aust U., Steurer M., Hall G., Huber L. (2014) Touchscreen performance and knowledge transfer in the red-footed tortoise (*Chelonoidis carbonaria*). *Behavioural Processes* 106: 187–192.

Niessing M., Berger M., Burchard L., Calapai A., Heisig K., Stephan V., Treue S., Gail A. (2015) Cage-based automated learning of cognitive tasks for rhesus macaques. Poster presented at the 11th Göttingen Meeting of the German Neuroscience Society, March 2015, Göttingen, Germany.

O'Hara M., Huber L., Gajdon G.K. (2015) The advantage of objects over images in discrimination and reversal learning by kea, *Nestor notabilis. Animal Behaviour* 101: 51–60.

Perdue B.M. (2016) The effect of computerized testing on sun bear behavior and enrichment preferences. *Behavioral Sciences* 6: 19–29.

Perdue B.M., Clay A.W., Gaalema D.E., Maple T.L., Stoinski T.S. (2012a) Technology at the zoo: the influence of a touchscreen computer on orangutans and zoo visitors. *Zoo Biology* 31: 27–39.

Perdue B.M., Stoinski T.S., Maple T.L. (2012b) Using technology to educate zoo visitors about conservation. *Visitor Studies* 15: 16–27.

Pons P., Jaén J., Catalá A. (2015) Envisioning future playful interactive environments for animals. In: A. Nijholt, ed., *More Playful User Interfaces: Interfaces that Invite Social and Physical Interaction*, pp. 121-150, Springer. http://doi.org/10.1007/978-981-287-546-4_6.

Savage-Rumbaugh S., McDonald K., Sevcik R.A., Hopkins W.D., Rubert E. (1986) Spontaneous symbol acquisition and communicative use by pygmy chimpanzees (*Pan paniscus*). *Journal of Experimental Psychology*: General 115: 211–235. doi:10.1037/0096-3445.115.3.211

Schmidjell T., Range F., Huber L., Virányi Z. (2012) Do owners have a Clever Hans effect on dogs? Results of a pointing study. *Frontiers in Psychology* 3: 558.

Schmitt V., Pankau B., Fischer J. (2012) Old world monkeys compare to apes in the Primate Cognition Test Battery. *PloS ONE* 7: e32024.

Sonnweber R., Ravignani A., Fitch W.T. (2015) Non-adjacent visual dependency learning in chimpanzees. *Animal Cognition* 18: 733–745.

Steurer M.M., Aust U., Huber L. (2012) The Vienna comparative cognition technology (VCCT): an innovative operant conditioning system for various species and experimental procedures. *Behavior Research Methods* 44: 909–918.

Thornton A., Lukas D. (2012) Individual variation in cognitive performance: developmental and evolutionary perspectives. *Philosophical Transactions of the Royal Society B: Biological Sciences* 367: 2773–2783.

Tomasello M., Call J. (2011) Methodological challenges in the study of primate cognition. *Science* 334: 1227–1228.

Ross S.R. (2009) Sequential list-learning by an adolescent lowland gorilla (*Gorilla gorilla gorilla*) using an infrared touchframe apparatus. *Interaction Studies* 10: 115–129.

Vonk J. (2003) Gorilla (*Gorilla gorilla gorilla*) and orangutan (*Pongo abelii)* understanding of first-and second-order relations. *Animal Cognition* 6: 77–86.

Vonk J. (2016) Advances in Animal Cognition. *Behavioural Sciences* 6: 27; doi:10.3390/bs6040027

Vonk J. Beran M.J. (2012) Bears “count” too: Quantity estimation and comparison in black bears (*Ursus americanus*). *Animal Behaviour* 84: 231–238.

Waller B.M., Whitehouse J., Micheletta J. (2016) Macaques can predict social outcomes from facial expressions. *Animal Cognition* 19: 1031–1036.

Webber S., Carter M., Sherwen S., Smith W., Joukhadar Z., Vetere F. (2017) Kinecting with Orangutans: Zoo Visitors’ Empathetic Responses to Animals’ Use of Interactive Technology. *Proceedings of the 1st Conference of Human-Computer Interactions*, CHI 2017, May 2017, Denver, CO.

Wirman H. (2013) Orangutan play on and beyond a touchscreen. In: Cleland, K., Fisher, L. Harley, R. (Eds.) *Proceedings of the 19th International Symposium of Electronic Art, ISEA 2013, Sydney*. Available at http://hdl.handle.net/2123/9678 (accessed 17 April 2017).

Whitehouse J., Micheletta J., Powell L.E., Bordier C., Waller B.M. (2013) The impact of cognitive testing on the welfare of group housed primates. *PLoS ONE* 8: e78308.

Whitehouse J., Waller B.M., Chanvin M., Wallace E.K., Schel A.M., Peirce K., Slocombe K. (2014) Evaluation of public engagement activities to promote science in a zoo environment. *PLoS ONE* 9: e113395. https://doi.org/10.1371/journal.pone.0113395

Whiten A. (2017) A comparative and evolutionary analysis of the cultural cognition of humans and other apes. *The Spanish Journal of Psychology* 19: doi:10.1017/sjp.2016.99.

Yamanashi Y., Hayashi M. (2011) Assessing the effects of cognitive experiments on the welfare of captive chimpanzees (*Pan troglodytes)* by direct comparison of activity budget between wild and captive chimpanzees. *American Journal of Primatology* 73: 1231–1238.

Zeagler C., Zuerndorfer J., Lau A., Freil L., Gilliland S., Starner T., Jackson M.M. (2016) Canine computer interaction: towards designing a touchscreen interface for working dogs. In *Proceedings of the Third International Conference on Animal-Computer Interaction* (p. 2), Milton Keynes, UK.