LemurLounge: Lemurs’ Individual-Level, Group, and Cross-Species Use of an Interactive Audio Device in Zoos

Vilma Kankaanpää
vilma.kankaanpaa@glasgow.ac.uk
University of Glasgow
Glasgow, UK

Fay E Clark
fay.clark@bristol.ac.uk
University of Bristol
Bristol, UK

Ilyena Hirskyj-Douglas
ilyena.hirskyj-douglas@glasgow.ac.uk
University of Glasgow
Glasgow, UK

Figure 1: The device in situ. From left to right, enclosure 1’s device from a visitor’s perspective, the system’s dimensions and the positioning of its infrared sensors, and a side view of enclosure 2’s implementation.

ABSTRACT
Computer technology for animals is typically oriented toward isolated individuals, seldom attending to such group-living factors as accommodating differences between individuals. To address this shortcoming of research and practice, the authors designed and developed an audio-based system that lets lemurs in group accommodation voluntarily trigger audio via a novel device dubbed LemurLounge and listen to it on their own. This interactive system was deployed for 14 lemurs, of three species (black-and-white, brown, and ring-tailed), in their normal habitat. The device’s presence clearly influenced lemurs’ visits to the relevant portion of the enclosure. Alongside a general preference for audio over silence, assessment of individual- and species-level differences revealed significant differences at both levels, though no particular sound type (rainfall, traffic, either upbeat or relaxing music, or white noise) was favoured. The findings and design work highlight the need for customisable and adaptive computer technology for animals living in group settings, with important implications for lemurs and other primates, humans included.

CCS CONCEPTS
• Human-centred computing → User interface design.

KEYWORDS
animal–computer interaction, lemur, audio, proximity, animal enrichment

ACM Reference Format:

1 INTRODUCTION
Non-human animals (‘animals’ from here on) are increasingly exposed to interactive computer systems, especially in settings of captivity such as zoos (whether traditional zoological gardens or aquarium facilities, safari parks, or sanctuaries), farms, laboratories, and domestic households. Many of these systems are deployed for the animals’ use. Spurred on by the manifesto for animal–computer interaction (ACI) [41], researchers have begun to design interactive systems for the needs of the animals themselves rather than purely for the human caretakers/researchers [27]. While these steps mirror early progress in approaches to human–computer interaction (HCI), which brought the user’s needs to the fore, ACI must account for much more extensive biological variation (e.g., between species in the animal kingdom) while also considering the ethics implications of captive or semi-captive animals participating in research [32].
The overarching intention behind ACI research is to facilitate animals’ more autonomous choice and control over their environment \cite{7, 28, 46, 54}. Thus far, most studies in this domain have created bespoke computer interfaces that provide novel stimuli for animals \cite{11, 22, 24, 31, 46, 53}. With their focus typically restricted to a handful of animal species and to small groups, of 1–5 users \cite{11, 20, 38}, designers of animal–computer interfaces generally restrict themselves to meeting the needs of a single individual \cite{22, 31} or, with a more utilitarian orientation, to overall suitability for the group \cite{24, 28}. In both cases, the core ethos is a sound one: designing technology centred on the user rather than the designer \cite{41}. This carries over from HCI work, wherein developers strive for technology that meshes with the users’ psychological traits, attending especially to their thoughts, feelings and behaviours \cite{2} – in the words of Rogers et al. \cite{61}, ‘making technology do what they want in ways that make sense to them’.

Acknowledging that the users act within a social milieu is inherent to this design process. Early on, HCI developers devoted considerable attention to designing technology that could be shared by heterogeneous users at the societal level \cite{5}. More recently, they have started directing their focus toward individuals, by investigating bespoke systems for users with special needs, such as young children \cite{56} or people identifying as neurodiverse \cite{17}. Supporting individuals via technology helps them live more autonomous, unique, creative, and self-determined lives \cite{68} and has been identified accordingly as among the ‘seven grand challenges of HCI’ \cite{67}.

Likewise, research in the ACI field has begun to reveal salient differences in how animals perceive and respond to technology \cite{12, 19, 44, 50, 62, 70, 73}. These distinctions have been observed at many scales across animal phylogeny, from taxa such as families down to species level \cite{4, 58, 59, 62, 73}. Simultaneously, social factors such as groups’ age/sex structure and dominance hierarchy exert an influence on animals’ responses \cite{24, 50}. Individuals’ character too may play a role in how animals access computer systems \cite{16}, although little work has examined this.

While ACI researchers’ work often centres on zoo animals, perhaps owing to the large number of species available for study (a zoo houses around 400 species, on average \cite{66}), several confounding factors are bundled with this setting’s accessibility. Among the challenges are that the animals are housed in view of the public and often live in ‘mixed-species enclosures’ intended to represent a particular habitat (e.g., a rainforest or coral reef) or designed to suit a particular biological trait (e.g., nocturnal activity) \cite{71}. To develop systems suitable for such occupants, ACI researchers must grapple with designing computer interfaces for a given enclosure’s multiple species – which may differ vastly in motivations and sensory, dietary, and social needs. This challenge has gone largely unaddressed, however. Since most ACI research has studied only individuals or small groups representing a single species, it has long remained unclear how a beneficial multi-species computer might operate.

Systems intended for animals’ benefit are often conceptualised in terms of enrichment, a notion that refers to a purposeful change in a captive animal’s environment in pursuit of some sort of welfare benefit \cite{48, 64}. Enrichment efforts for zoo-housed primates in particular have received extensive research attention, with these animals’ ACI-based enrichment having focused on audio and visual stimuli especially \cite{21, 53, 58, 75}. All this attention notwithstanding, results have been mixed and highly inconclusive. While there is an association between audio (more precisely, acoustic stimuli consisting of playback of pre-recorded audible sound) and improved welfare in several primate species \cite{59}, we do not yet know what types of audio confer the greatest benefits. So far, comparisons across types of audio content, primarily involving evaluating preferences by means of animals choosing between two or more audio types, have found wide variation in preference levels between species, groups, and individual primates. For instance, while zoo-housed Western lowland gorillas (Gorilla gorilla gorilla) in a study by Robbins and Margulis \cite{59} seemed to prefer natural sounds (i.e., sounds produced in nature), Truaux and Vonk’s work \cite{70} found gorillas to prefer silence and unnatural sounds\footnote{In the strictest sense, silence exists only in a sound-pressure vacuum. Our use of the term as shorthand for conditions of no audio provision or of only ambient/background noise is consistent with prior literature.}. Findings with several other primate species support concluding that silence is favoured over sounds: Sumatran orangutans (Pongo abelii) \cite{58}, cotton-top tamarins (Saguinus oedipus), and common marmosets (Callithrix jacchus) \cite{43} display this tendency. However, white-faced saki monkeys (Pithecia pithecia) have chosen traffic noises not just over other (natural and unnatural sounds) but also in preference to silence \cite{53}. Some research examining several species of primates suggests that audio elicits positive behavioural responses more generally \cite{6, 35, 52, 72}, while other work points in the opposite direction \cite{59, 73}.

Several ACI researchers have speculated that the variation detected in primates’ responses to audio might well arise from method-related differences between studies \cite{53}. Most researchers have piped audio recordings directly into animal enclosures \cite{50, 65, 73}; very few have developed interfaces that give the animals some choice over which content they listen to, at what time \cite{28, 53, 58, 70}. Even in the latter conditions, the sound still has often been broadcast to the entire group rather than the individual selecting it. Moreover, interface mechanisms are dotted along a broad spectrum: some primates have accessed an on-screen interface via a stylus \cite{58}, others have been given a touchscreen interface for the hand/finger \cite{70}, and a few settings feature computers utilising data from motion sensors \cite{53}. Understandably, this landscape renders it very difficult to generalise results and to distinguish the effect of interacting with a computer from that of the audio content, of whatever type. Matters grow even trickier when one has to address the cognition, behaviour, and hearing differences that have evolved in particular species.

Clearly, far more methodical research is necessary to shed light on computer-interface use across larger single- and mixed-species groups, affording valid direct comparison by applying the same system and methods. Considering multi-species groups’ use of computers is especially important as mixed-species enclosures are commonplace at the majority of zoos. We set out to fill this gap by designing a computer device for three co-housed species of lemurs of the Lemuridae family.

We chose lemurs because 1) they are popular and commonplace at zoos yet, to our knowledge, 2) no audio-device studies had thus far considered them. To address the above-mentioned shortcomings
of prior work, we devised an interactive device that lemurs can voluntarily trigger by moving within the device so that it plays several types of audio material for them to listen to under otherwise normal conditions (i.e., they maintain their normal social housing and management routines). Following established ACI practice (specifically from audio-enrichment studies), we tested lemurs’ preferences by tracking the frequency of triggering the device and the time the animals chose to spend interacting with the device. Our study addressed two central research questions:

RQ1: What audio do lemurs prefer to listen to?
RQ2: Do lemurs’ interactions with an audio device differ between individuals or by species?

While drawing from prior research into animals’ preferences, our investigation of audio-device interaction by group-living primates advances research decisively. Through a concrete demonstration of technology for animals that caters both for individual-level preferences and for needs at family, species, and single-user levels in a zoo setting, our novel contribution encourages and presents a strong argument for developing practical technology for testing preference across species boundaries in a normal social setting. For the ACI community, this paper heralds a new era of designing interfaces for social animals – a break with the status quo of designing for homogeneous groups or isolated individuals. The implications also extend to HCI: we need to ask what ‘personalisation’ of interfaces really means and whether it is truly possible for non-humans and humans alike. Through work with non-verbal users, ACI research holds the potential to inspire and inform HCI efforts toward addressing diverse human users, from pre-verbal children, through adults with less typical means of feedback and computer use, to people with diminished faculties as their life draws to a close.

2 RELATED WORK
Technology has rapidly progressed and is growing more and more enmeshed with human living and the day-to-day life of animals acting in human contexts. Our work is anchored both in research from the field of HCI and in investigations of how animals engage with computerised technology and how this technology can be adapted to their individual-specific needs [41]. Below, we lay out the background to our research by looking at audio enrichment for primates and how computers have been developed for individual users – humans and animals. This includes considering ways in which technology can promote animals’ expression of natural behaviours [64] and the behavioural competencies they display in nature [13].

2.1 Auditory Enrichment for Primates
Many writings over the years have recommended audio stimuli as a technique for bringing variety to environments of captivity [77]. These proposals are rooted partially in music and other sounds’ contributions to human well-being [77]. While some literature reports on efforts to identify potential benefits and impacts of audio enrichment specific to non-human primates [70], these efforts have yielded varied, often mutually contradictory results [77].

The blame might lie partly in the approach to zoo-audio studies. Typically, rather than let the animal engage with a computer interface to control audio output, the researcher controls the sound; moreover, it gets broadcast to the whole group without giving them a choice. In contrast, what genuine ACI-oriented audio research has been performed to date is directed toward systems that animals can autonomously turn on and off. The computer-enabled audio devices developed for primates thus far have utilised tangible objects that, when manipulated by orangutans, trigger sounds without (as a musical instrument does) generating any sound themselves [54]; touchscreens with which orangutans and gorillas may select audio or silence [58, 70]; and proximity-based interfaces for white-faced sakis’ triggering of audio output [53].

As those projects illustrate, music has been the most popular choice of auditory content for non-human primates. The literature does not make the reasons for this entirely clear; they might stem from our own preference for music or even be arbitrary [40]. Alongside music content (most characterised as ‘classical’, though Western ‘pop’, rock, and electronic genres too get employed [45, 53, 59, 73]), other categories of audio have been natural sounds such as rain or immersive soundscapes of forests [59, 70] and, used less often, anthropogenic sounds – road traffic [53] and other human-made sounds. Finally, white noise frequently features in such research, for what it might reveal about whether animals discriminate between purposeful audio and ambient noise or even distinguish more finely among features of sound [40].

The effects of audio on primate behaviour vary considerably within and across species boundaries. For example, playing commercial radio stations’ combinations of popular songs and speech has been linked with improved welfare among baboons (Papio spp.) [6], chimpanzees (Pan troglodytes) [72], and rhesus macaques (Macaca mulatta) [52]; however, researchers also have found an association with both higher [35, 59] and lower [59, 73] levels of abnormal behaviour in great apes. Natural sounds such as forest soundscapes, in turn, have correlated with increased arousal in gorillas [50], but it is unclear whether this is best interpreted as a positive vs. a negative welfare outcome. Some researchers have posited that audio stimuli function as a mask, covering up the ambient noise of the animals’ surroundings [76], and evidence exists that natural sounds indeed mask ambient noise’s negative effects on infant gorillas [50] and reduce stereotypy in adults of the species [59].

When able to express their preferences, primates have often favoured silence over audio stimuli [43, 58, 70]. Here too, even intra-species results prove inconclusive – for instance, gorillas may prefer silence and unnatural sounds to natural sounds [70], or they may prioritise natural sounds over other types of audio [59]. Chimpanzees, in turn, have favoured music over silence [45], while saki monkeys preferred traffic noise to both these and silence [53]. Some primates have behaved with indifference to multiple types of audio [74, 76].

2.2 Inter-User Differences and Personalising Computer Systems
The foregoing discussion points to the knottiest issue of prior audio-response research with primates: a murky picture emerging from
the vast range of methods applied. Great variations in study duration, audio-stimulus types and timings, metrics for dependent variables (animals' responses), etc. certainly speak to the value of research with more methodological standardisation. At the same time, though, we must not overlook the need to recognise concrete differences within and between primate groups and measure these accurately. Firstly, one can reasonably presume that these species display meaningful differences in audio responses that arise from biological factors [59]. Body size, diet, mating patterns, and habitat all have precipitated differences in auditory systems within the primate order, which extends from tiny mouse lemurs to large great apes. Secondly, important differences are bound to exist between individuals in a given species and/or group. This notion, by no means new, dovetails with a keen awareness of divergences in how individual humans think and feel. These constitute a major component of modern psychology [9]. Accordingly, personal differences in technology use and development form a core theme of the ACM Conference on Human Factors in Computing Systems.

Humans’ technology use is known to differ by culture and with demographic factors such as sex, gender, and age [51, 57]. Therefore, researchers possess both the motivation to develop personalised interfaces and the tools to do so as advances permit more sophisticated interfaces. Modelling user-specific behaviours enables the user to make adjustments (with ‘adaptable’ user interfaces) and, alternatively, automatic adjustments based on the individual and context (with ‘adaptive’ interfaces) [1, 69]. The input for these changes can be modelled/measured through users’ implicit behaviours (e.g., social-media entities recommending videos that members of the relevant population frequently view or ‘like’) and explicit actions (e.g., tailoring the recommendations via analysis of what the user in question has watched). Interfaces of this sort can inform the creation of personalised profiles that account for the user’s needs, preferences, skills, and environment [25].

Since building machines that understand people is articulated as a key goal for current HCI research [36], the question arises of how we can develop computers for animals that recognise their individuality and their group membership. Though ACI work has attended extensively to designing for individuals [10, 55, 60, 63], it has not examined ways to address their needs in the context of technology for group-living animals. Redressing this shortcoming could unveil how the extensive body of HCI knowledge could inform work with other non-human species in interaction-design contexts. Furthermore, exploring how individuals who live in groups use interfaces differently, whether human or not, advances both animal computing and HCI research. Yet, in the absence of larger-scale studies and work with identical conditions across species, the extent of the species- and individual-specific differences remains unknown. We addressed this gap by investigating the preferences within a group of lemurs representing three species (RQ1) and the variation in their preferences by species and between individuals (RQ2).

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3 PARTICIPANTS

Fourteen individual lemurs participated in the study, conducted in a facility in Scotland, at Blair Drummond Safari Park and Zoo. The species of Lemuridae lemurs studied were the black-and-white ruffed (Varecia variegata), common brown (Eulemur fulvus), and ring-tailed (Lemur catta) (see Table 1). All individuals had been born in captivity. Participant P4 was the mother of P6 and half-sister (on the maternal side) to P5, and P7 and P8 were the parents of P9–P14. This 14-participant study, which lasted 56 days, provided a significant sample size by ACI and zoo-animal-study standards. Moreover, typical ACI studies of primates have been far shorter than ours (e.g., two weeks long) [70, 75]. Hence, our dataset and findings stand out further as a substantial contribution to research attending to how primates engage with computer interfaces.

The physical setting of the study, which took place in August–December 2022, involved lemurs housed in two adjacent enclosures (shown in Fig. 2). Enclosure 1 housed animals of all three species, while only black-and-white lemurs occupied enclosure 2. Each enclosure contained indoor structures, where our system was deployed, and outdoor area providing shelters, wooden climbing frames, and naturally growing trees and other vegetation. The enclosure-1 lemurs shared their outdoor areas with six Patagonian maras (Dolichotis patagonum), and the second enclosure’s lemurs shared theirs with three domestic sheep. Visitors too were present.
in these shared areas: a walking path for guests wound through both outdoor spaces.

4 ETHICS
The lemurs’ participation in the study was entirely voluntary: they could choose whether to interact with the device or not. Moreover, it did not obstruct their general movement or access to resources in the enclosure. Keepers maintained the animals’ normal management routine, and none of them were food- or water-deprived. Experiment procedures complied fully with Association for the Study of Animal Behaviour (ASAB) guidelines for the treatment of animals in behavioural research [3], and our project received ethics approval from Blair Drummond Safari Park and Zoo’s research board and the University of Glasgow’s Vets Research Ethics Committee (Ref 28/22).

5 THE AUDIO DEVICE
In collaboration with the lemurs’ keepers, we specified the requirements for the audio-enrichment device. These were similar to those identified for other zoo-housed primates [30], including 1) humans can easily access the device, 2) humans can monitor the device, 3) the lemurs do not need training in its use, 4) the device is durable for animal use, and 5) the device does not have negative effects. In addition, the keepers expressed a desire for autonomous operation, to minimise the work required of them, and asked that it not operate during the night.

We developed the audio-enrichment device, ‘LemurLounge’, to address these requirements and give the lemurs freedom to control its activation and the type of audio content. Adapting a design devised by Piitulainen and Hirskyj-Douglas [53] for white-faced saki monkeys provided an appropriate system that met our requirements. Figure 1 presents its structure. Movement in a tunnel-shaped device positioned within the lemurs’ normal enclosure afforded them easy proximity-based control of the audio. The device was triggered when a lemur entered and promptly switched off when the animal left it. This was accomplished using three infrared sensors. We used wood for the walls and flooring of the ‘lounge’ since it was a familiar material typical of their enclosure. Wood also prevented slipping and could withstandlemurs’ mouth action, defecation, and other everyday behaviour. We equipped the device with a transparent polycarbonate lid (3 mm thick) to prevent the lemurs from feeling enclosed. The technology was concealed safely in a watertight container behind the system’s side wall, where it could be accessed for maintenance by researchers and keepers via a locked sliding door (which lemur could not open). In each enclosure, the device was installed on a shelf such that lemurs’ access to other resources was not blocked and for a good video-camera view. Also, raising the system from floor level was consistent with the lemurs’ normal activities, which were frequently above ground height. In further adjustments, we increased the device height from that in the saki-monkey design to accommodate the lemur species’ larger body size and their longer tails, with measurements suitable even for the largest lemur (P1). We also chose sturdier materials, to ensure sufficient structural strength for withstanding any pushing, leaning, or sitting/standing actions by lemurs.

5.1 Audio Stimuli
Once triggered, the audio continued as long as a lemur was inside the device. It played in a continuous loop (a single audio track being 3.5 minutes long on average), which resumed when next triggered by a lemur. To address the absence of data on lemurs’ audio preferences, we selected a variety-rich set of sounds, both artificial and naturalistic, covering these audio types: rain, traffic, ‘upbeat’ music, ‘calm’ music, and white noise. While comparing hearing faculties between species is immensely complex, we bore in mind that lemurs hear high frequencies better than humans do [14, 26]. For simplicity’s sake, we opted for five sound types that differed substantially from each other in frequency while still being audible to lemurs and humans. We deemed rain a fitting choice for a sound relatively familiar to the lemurs, since they could move about outdoors and had exposure to the elements. In contrast, the other sounds were likely to be unfamiliar, in light of the zoo’s fairly remote countryside location and keepers’ comments that the lemurs had not, to their knowledge, been exposed to music on the radio. We would describe the sounds thus, with the caveat that we cannot know how well lemurs’ perceptions match our subjective human characterisation: The rain audio was largely uniform and showed little temporal variation, apart from occasional ‘splat’ sounds of individual droplets. Overall, its spectrum was close to a pink-noise profile. Our second track, the traffic audio, was recorded at a busy urban location in India, with a soundscape including vehicle horns honking, motor/engine sounds, and a general background industrial hum. This track showed the greatest variety, with distinct temporal variations in noises such as honking against uniform background noise. The ‘upbeat’ music was electronically generated to provide a clear melody, rhythmic bass beat, and high tempo. Of all the sounds, this displayed the most prominent temporal variation. It had a more varied spectrum than the other music track, the ‘calm’ music. The latter audio consisted of a hybrid of electronic and instrumental sounds, with a melody far less detectable than the other music’s. Overall, the spectrum of this track, which featured occasional brief segments of wind-chime-like and string-instrument sounds, was more varied than the rain one, but its temporal variation was still mild, with no sudden loud sounds. For the fifth track, we utilised white noise, in keeping with routine practice for standardised baseline sounds in auditory-enrichment research with animals [40]. In addition, the study included a ‘silent’ condition, wherein no sound was played by the device but ambient background noise remained present.

5.2 Hardware and Software
LemurLounge relied on software written in Python 3 running on a Raspberry Pi 3 Model B. The software is available from GitHub. The Raspberry Pi handled triggering of the audio content when a lemur’s presence activated the infrared sensors (Sharp GP2Y0A1SKOF, 4–30 cm), which were positioned to capture motion by the smallest lemur and thereby create a continuous interaction space within the tunnel. The audio was emitted by a speaker unit fixed to the side of the device (a Pi Hut USB speaker). The volume for all audio was set to between 45 and 60 decibels inside the device. For ethical

We followed the study procedure once in each enclosure, for all its lemur occupants (see Table 1). From each enclosure, data were collected over 56 days, representing responses in three conditions: a baseline without the device present (the first week), interaction with audio (42 days), and post-exposure (the final week). Although researchers’ baseline data often have come from settings of computer/enrichment devices installed without any stimuli (i.e., switched off) [28, 29, 53], said approach with non-human primates can be argued against. Prior work with non-human primates for interactive audio devices [39] has recommended against introducing non-live versions of computer enrichment systems for the baseline period. It has been suggested that the change from live to non-live is potentially unclear to primates biasing the results, i.e., simply turning on a device without any other changes does not make it obvious that the device is now interactive. Data quality could be expected to suffer accordingly. Therefore, for seven days, we recorded all visits to the portion of the enclosure where the device was later to be installed. We denote this location as the interaction space; hence, our comparisons across conditions refer to lemurs’ interactions within that location, with or without the device, while ‘device interactions’ refers specifically to engaging with the active device during the 42 days after the baseline period. For the post-exposure condition, we removed the device to measure how the system affected interactions in the lemurs’ living area. In line with practices followed across multiple animal species to ascertain the long-term effects of computer-based enrichment, we applied the procedure used for the baseline condition (measuring the lemurs’ visits to the location where the device had been) to judge the after-effects of the stimuli [29, 33].

The audio device was programmed to play only one type of audio on any given day, cycling through the five types and silence. This approach enabled evaluating whether lemurs voluntarily returned to the device to listen to sounds of a known type. Had the device cycled (randomly or otherwise) through multiple sounds per day, it would have been difficult to ascertain whether participants triggered the device to listen opportunistically to any sound vs. to hear a particular sound. We used a crossover study design for the five audio types plus silence, repeating each sound seven times in a random order without replacement, to mitigate any order effects.

With each audio type, the system recorded interaction data when the device was turned on, between 6 am and 6 pm. It would have been too dark to verify interactions during the night, but the device was left installed for practical reasons (not least to minimise disturbance to the lemurs and to meet the keepers’ requirements). We were interested in how often the lemurs engaged with the system (interaction frequency) and how long the interactions lasted (their duration). Video footage from the enclosure-mounted camera in the pre- and post-audio conditions recorded relevant lemur interactions within the interaction space. Details of each interaction (date and time, duration, species, and individuals) occurring within this area were coded into an online spreadsheet. We anticipated a possible influence of ambient weather conditions on lemur responses because such patterns have been noted in chimpanzees using computer-based enrichment [79]. Therefore, we obtained weather data for each day of the study4 and logged the study location’s mean average temperature (in °C) between 6 am and 6 pm. There was no device downtime at any point during the study, and keepers reported no health or safety concerns.

6 METHOD AND DATA ANALYSIS

We followed the study procedure once in each enclosure, for all its lemur occupants (see Table 1). From each enclosure, data were collected over 56 days, representing responses in three conditions: a baseline without the device present (the first week), interaction with audio (42 days), and post-exposure (the final week). Although researchers’ baseline data often have come from settings of computer/enrichment devices installed without any stimuli (i.e., switched off) [28, 29, 53], said approach with non-human primates can be argued against. Prior work with non-human primates for interactive audio devices [39] has recommended against introducing non-live versions of computer enrichment systems for the baseline period. It has been suggested that the change from live to non-live is potentially unclear to primates biasing the results, i.e., simply turning on a device without any other changes does not make it obvious that the device is now interactive. Data quality could be expected to suffer accordingly. Therefore, for seven days, we recorded all visits to the portion of the enclosure where the device was later to be installed. We denote this location as the interaction space; hence, our comparisons across conditions refer to lemurs’ interactions within that location, with or without the device, while ‘device interactions’ refers specifically to engaging with the active device during the 42 days after the baseline period. For the post-exposure condition, we removed the device to measure how the system affected interactions in the lemurs’ living area. In line with practices followed across multiple animal species to ascertain the long-term effects of computer-based enrichment, we applied the procedure used for the baseline condition (measuring the lemurs’ visits to the location where the device had been) to judge the after-effects of the stimuli [29, 33].

The audio device was programmed to play only one type of audio on any given day, cycling through the five types and silence. This approach enabled evaluating whether lemurs voluntarily returned to the device to listen to sounds of a known type. Had the device cycled (randomly or otherwise) through multiple sounds per day, it would have been difficult to ascertain whether participants triggered the device to listen opportunistically to any sound vs. to hear a particular sound. We used a crossover study design for the five audio types plus silence, repeating each sound seven times in a random order without replacement, to mitigate any order effects.

With each audio type, the system recorded interaction data when the device was turned on, between 6 am and 6 pm. It would have been too dark to verify interactions during the night, but the device was left installed for practical reasons (not least to minimise disturbance to the lemurs and to meet the keepers’ requirements). We were interested in how often the lemurs engaged with the system (interaction frequency) and how long the interactions lasted (their duration). Video footage from the enclosure-mounted camera in the pre- and post-audio conditions recorded relevant lemur interactions within the interaction space. Details of each interaction (date and time, duration, species, and individuals) occurring within this area were coded into an online spreadsheet. We anticipated a possible influence of ambient weather conditions on lemur responses because such patterns have been noted in chimpanzees using computer-based enrichment [79]. Therefore, we obtained weather data for each day of the study4 and logged the study location’s mean average temperature (in °C) between 6 am and 6 pm. There was no device downtime at any point during the study, and keepers reported no health or safety concerns.

6.1 Handling and Analysis of the Data

Preparing the data for analysis consisted of video verification and cleaning, coding, and statistical analysis involving visualisations and comparison tests. In all, 2,075 separate device interactions were

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4From the online archives of https://www.timeanddate.com/.
logged. We excluded interaction triggered accidentally, whether through peculiarities of the device itself or by an insect, humans testing or cleaning the device, etc. (249 interactions). For the 1,826 lemur interactions that remained, we coded the species and individual ID associated with each from the video recordings. As for the pre- and post-audio conditions, we observed 138 and 392 interactions in the space where the device would be and had been installed, respectively.

The extent of data logging varied from day to day and between the enclosures, partly for reason of changes to zookeeper schedules that were outside our control (affecting actual device on/off times) and unequal lemur-group sizes (see Table 1). To account for this, we converted the data to relative values: For each day, we divided the total count of interactions and the sum-total interaction duration by the number of observation hours and the number of lemurs. Examining differences across species and between age groups necessitated further adjustments for group size. In consequence, the paper presents analyses in terms of interactions per hour per lemur (frequency) and amount of use per hour per lemur, in seconds (duration), with each study day yielding one value. The distributions of interaction frequency and duration are right-skewed rather than normally distributed, so we refer to the median (MD) and interquartile range (IQR) to characterise the data and non-parametric statistical tests.

We performed data analysis at three levels: for the full group (the lemurs in both enclosures as a zoo-level sample), by species, and for individuals. With each of these levels, we compared between the three conditions (pre-audio, audio, and post-audio) and between audio sources (rain, traffic, each of the music types, white noise, and silence), examining both frequencies and durations. Only the lemurs in enclosure 1 (P1–P6) could be identified as specific individuals, so individual-level analyses were confined to that enclosure’s occupants. We performed a Kruskal–Wallis test for the initial detection of any significant differences in median values when making the condition and audio-type comparisons, followed by a pairwise Dunn’s test (with the Holm method for adjusting p-values) for multiple pairwise comparisons. For testing audio in general to silence, we used the Wilcoxon rank sum test (Mann–Whitney U-test). Finally, we examined correlations (plotting ambient outdoor temperature vs. use of the interaction space and lemurs’ age vs. device interactions) employing Kendall’s tau rank test. All statistical analyses were performed with RStudio IDE software (v. 2022.12.0+353) with the libraries tidyverse (v. 1.3.2) for descriptive statistics, ggpubr (v. 0.5.0) for the Kendall correlation test, rstatix (v. 0.7.1) for the Kruskal–Wallis and Dunn’s tests, and coin (v. 1.4-2) for the Wilcoxon test. The results hence represent a combination of descriptive and statistical tests.

7 RESULTS

When the device was first introduced, we did not observe any neophobia (fear or aversion). Several behaviours took place within the device (most commonly walking but also grooming, sleeping, and resting). At times, the lemurs interacted socially within the device (i.e., with conspecifics). However, it is worthy of note here that sometimes it was a lemur’s tail rather than the body that triggered the device (equally, a tail-swipe within the interaction space was enough to be recorded as use of the interaction space in baseline and post-stimuli conditions).

<table>
<thead>
<tr>
<th>Table 2: Exposure’s effect on the use of the interaction space, for each of the lemur species.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Interactions/h</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Baseline</strong></td>
</tr>
<tr>
<td><strong>Audio-interaction</strong></td>
</tr>
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<td><strong>Post-exposure</strong></td>
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<tr>
<td><strong>Time/h (s)</strong></td>
</tr>
<tr>
<td><strong>Baseline</strong></td>
</tr>
<tr>
<td><strong>Audio-interaction</strong></td>
</tr>
<tr>
<td><strong>Post-exposure</strong></td>
</tr>
</tbody>
</table>

7.1 Group-Level Analyses

On average, a lemur exposed to the audio-interaction condition engaged with the device 3.1 times per day, for 28.5 seconds in total. The lemurs’ interactions with it were typically short, with the median value (MD) being four seconds (IQR = 6 s) and the range stretching from a single second to 13.4 minutes. The number of interactions with the device in enclosure 1 rose slightly throughout the study while the lemurs in enclosure 2 engaged most on the first day of operation, after which their interaction level fell before climbing again, over days 8–49 (see Fig. 5). We found that temperature correlated with lemurs’ use of the interaction space: both interactions per hour and engagement duration increased when the temperature outside fell (frequency: weak correlation, tau=-0.22, p=0.00069; duration: weak correlation, tau=-0.13, p=0.039). This is consistent with evidence that ring-tailed lemurs spend more time inside when the environment is cold, wet, and darker [15]; however, the device’s introduction too may have contributed to the increase in frequency and duration.

**Effects of Interactive Audio.** The frequency of interaction-space use rose as the study progressed (as Fig. 6 attests), but not significantly. Lemurs spent more time in the interaction space on days before and after the device was in operation (baseline MD = 2.25 s, IQR=7.9; audio-condition MD = 1.80 s, IQR=2.0; and post-exposure MD = 11.8 s, IQR=14.7; see Fig. 6’s duration data). The lemurs used the interaction space significantly longer in the post-exposure condition than in the baseline one (p=0.026, z=2.48, eta²[H]=0.10: moderate effect) and relative to the audio-interaction condition (p=0.0003, z=3.89, eta²[H]=0.16: large effect).

**Audio Preferences.** The lemurs did not exhibit a preference for any particular audio type but did interact with the device significantly more often when it produced audio (MD=0.3, IQR=0.28; p=0.0096, z=2.6, r=0.28: small effect) as compared to silence (MD=0.15, IQR=0.20). Lemurs’ interaction duration too was significantly longer (p=0.0019, z=3.1, r=0.34: moderate effect) with audio output (MD = 1.9 s, IQR = 2.1 s) than with silence (MD = 0.65 s, IQR = 1.4 s).

7.2 Lemurs at Species Level

Clear differences emerged in how the individual species interacted with LemurLounge. The low number of participating brown and
Figure 5: Lemurs’ use of the interaction space, with the system operating (on days 8–49, at centre) and without the device (in day 1–7’s baseline condition and post-exposure, on days 50–56), throughout the study, represented in terms of use instances per hour per lemur. The two black loess curves characterise the results from the two enclosures (the solid line for Enclosure 1 and the dashed line for Enclosure 2).

We examined patterns in the length of individual device interactions also, finding that those among brown lemurs were shorter (MD = 2.0 s, IQR = 3.5 s) than ring-tailed lemurs’ (MD = 4.0 s, IQR = 1.5 s) or black-and-white lemurs’ (MD = 4.0 s, IQR = 7.0 s). Black-and-white lemurs engaged in the longest distinct interactions, as long as 13 minutes, while brown lemurs interacted with the lounge for up to 15 seconds and ring-tailed for up to 27 seconds.

Effects of Interactive Audio. The species exhibited varying responses to the audio device exposure, with differences observed in the time spent within the interaction space across study conditions and among species.

Black-and-white and brown lemurs typically used the interaction space for the most time in the post-exposure condition followed by the audio-interaction condition, while ring-tailed lemurs’ interaction durations were greatest in the baseline setting followed by post-exposure. In all three conditions, black-and-white lemurs exhibited more variation in the time spent in the space, relative to each of the other species (as the IQR for time per hour in Table 2 shows).

Audio Preferences. None of the three species showed a preference for any particular audio type. Comparing all audio to silence, brown lemurs diverged from the other species in interacting with the device more often and for a longer time when it produced silence (see Table 3).
Table 3: The effect of playing audio on lemurs’ interactions with the device, broken down by species.

<table>
<thead>
<tr>
<th></th>
<th>Black-and-white</th>
<th>Brown</th>
<th>Ring-tailed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Interactions/h</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Audio</td>
<td>69</td>
<td>23</td>
<td>14</td>
</tr>
<tr>
<td>Silence</td>
<td>8</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Time/h (s)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Audio</td>
<td>69</td>
<td>23</td>
<td>14</td>
</tr>
<tr>
<td>Silence</td>
<td>8</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 4: The interactions of each enclosure-1 lemur when the device was present.

<table>
<thead>
<tr>
<th>ID</th>
<th>Instances/h</th>
<th>Time/h (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Instances/h</td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td>42</td>
<td>7.90 5.75</td>
</tr>
<tr>
<td>P2</td>
<td>16</td>
<td>1.00 1.33</td>
</tr>
<tr>
<td>P3</td>
<td>6</td>
<td>2.10 2.08</td>
</tr>
<tr>
<td>P4</td>
<td>22</td>
<td>1.75 1.55</td>
</tr>
<tr>
<td>P5</td>
<td>18</td>
<td>1.20 1.20</td>
</tr>
<tr>
<td>P6</td>
<td>35</td>
<td>2.20 1.30</td>
</tr>
</tbody>
</table>

7.3 Lemurs As Individuals

We considered individual-specific aspects of lemurs’ interactions by examining the age factor. When audio was available, older lemurs engaged with LemurLounge more frequently (moderate correlation, with \(\tau=0.457, p<0.0001\)). Similarly, the duration of interactions rose with lemur age, though with only a weak correlation (\(\tau=0.255, p<0.0001\)). Black-and-white lemur P1 interacted with the device twice as often as P2–P6 and spent four times as much time in the lounge (see Table 4).

Effects of Interactive Audio and Audio Preferences. Exposure to the audio condition affected how individuals used the interaction space (as Fig. 7 elucidates). Of the six individuals we could identify in enclosure 1, five (P1–P4 and P6) used this space more often in the audio-interaction condition than in the baseline setting, and the final lemur (P5) did not change interaction frequency. Four individuals (P1, P2, P5, and P6) visited the space more often after the device was removed, while two (P3 and P4) used it less often in the final condition.

There are clear differences in how often individuals triggered the various audio types. Figure 8 presents examples of four individuals: P6 triggered music the most frequently and white noise the least, while P3 and P2 did exactly the opposite.
8 DISCUSSION

Our study of 14 zoo-housed lemurs’ responses to the novel audio-enrichment device LemurLounge marks a significant advancement in ACI and acoustic enrichment for animals. As far as we are aware, it represents the first project to design and implement a computerised system for lemurs and to look at audio within this context. More generally, it highlights the importance of, and challenges in, accommodating the normal biological variation in groups of animals housed together. The lemurs in our study responded differently to the audio device, as species and as individuals. We found clear differences in how long and how often they chose to interact with the device and in which type of audio they preferred (answering RQ2). Although we did not uncover a general-population preference for any particular audio type (answering RQ1), they showed an overall preference for audio over silence— but alongside individual- and species-level variations in audio preferences.

8.1 Differences between Species and among Individuals

LemurLounge’s impact on the interaction space’s use depended on the species and the individual. We found age to be a significant factor in distinctions between individuals. This finding supports evidence of an association between lemurs’ age and their use of touchscreens; older lemurs appeared to show slower learning and weaker performance in visual-discrimination and reversal-learning tasks while demonstrating greater perseverance [37]. Also, daily behaviour patterns of a given individual or species may explain some found differences. For instance, a lemur might favour specific areas of the enclosure at large leading to most interactions with the device, or a particular species might mostly move around the enclosure as a group, explaining their similar interactions.

Extending our examination beyond lemurs by comparing these species’ interactions with the audio-enrichment device to those of white-faced sakis\(^5\)[53], we found clear differences. White-faced sakis interacted with the equivalent device significantly longer per hour than lemurs did (lemur MD = 1.8 s, IQR = 2.0 s and saki MD = 3.2 s, IQR = 4.6 s; \(p=0.005, z=-2.8, r=0.26\), though the effect was small. Also, white-faced sakis preferred traffic sounds over rain sounds or either category of music [53]. Lemurs and white-faced sakis typically interacted with the device for the same amount of time: the median length for all interactions with the device was four seconds.

The differences detected at the levels of lemur species, individuals and between lemurs and sakis might go some way toward explaining the disparities visible in literature reporting on primates’ audio preferences. Analysis merely at the troop level does not capture some found differences. For instance, a lemur might favour specific areas of the enclosure at large leading to most interactions with the device, or a particular species might mostly move around the enclosure as a group, explaining their similar interactions.

8.2 Methodology for Assessing Intentionality and Preference in Lemurs

A key aspect of assessing differing responses to technological interventions and to computer-based stimuli is to reveal which aspects of the technology, the animals’ environment, and their life experiences caused the effects observed [34]. In zoos, where space is limited, there is an ethical imperative to look at the long-term impact of deploying computer systems that augment an animal’s home: we must know how the technologies affect animals. Lemurs are among the many animals that can be sensitive to changes in their environment [15]. Our results indeed attest that the device affected the lemurs’ movement within the space, which the lemurs occupied longer and visited more frequently once the device was removed—more than before it was introduced or with the device present. While the non-contraction in space use could indicate that the device had no long-term effects, the lemurs’ greater use of the interaction space after the device’s removal raises questions of its own. We speculate that the change in environment wrought by its removal sparked greater interest in the space. This intriguing result demonstrates the difficulty of balance between animals’ agency (choice to use the system) and humans’ (we were the ones who introduced the device and are responsible for considering any long-term effects). Measuring the consequences of our computer interventions and the meaning behind behaviour changes is often complex and charged with ethical dilemmas; we do not know the impact of what we are doing as scientists until we observe its effects.

Though the lemurs interacted with the device more often and longer when it produced audio than when silence ensued, we cannot understand an animal’s complete \textit{umwelt}\(^6\). The possibility exists...

\(^5\)For white-faced lemurs, we referred to data available via GitHub (see https://github.com/roosapi/music-for-monkeys). The lemur and saki data were normalised for the number of participants and the number of hours on each day of the study.

\(^6\)The term was popularised by Jakob von Uexküll to describe animals’ unique sensory bubble and their experience of the world [42].
that facets of the device we may have overlooked influenced interaction behaviour, such as its smell or other aesthetics, social meaning, or its ability to provide shelter.

Likewise, changing the space by requiring the lemur to enter the device to trigger audio could have influenced space use and the lemurs’ interaction behaviour. Recent work has highlighted the impact of modality on interaction frequencies and durations on zoo-housed animals’ use of computer devices [23]. This issue elevates the importance of ACI efforts grappling with what metrics and methods to use for evaluating animals’ experiences of computerised devices [10, 38, 60]. We chose space as an interaction trigger because it offers one of the simplest interaction interfaces, aligned with the aim to match the user’s intentions (manifested in space use) to the actions accessible (playing audio). A simplistic method was chosen to increase the chances of the lemurs understanding the device, and as such, their agency and control of the system. Studies show that simple mechanisms for choice and control over computer-delivered stimuli (heat and light) can enhance other zoo-housed primates’ welfare [7], irrespective of the stimuli provided. The option of having a choice in itself might be a factor behind the lemurs’ use of the device. Exercising choice and control implies that, on some level, the lemur understands the interface: the interaction loop entails a lemur exhibiting a behaviour, the computer recognising this behaviour and furnishing some output accordingly, and then the animal directly perceiving and interpreting that output. This loop has been termed the gulf of interaction in ACI, based on Norman’s theoretical framework [32, 42]. Gaps are understandable here, in that it is hard for humans to measure intentionality within animal behaviour, not least intention to use computer devices [78]. In the case of LemurLounge, which of the lemurs’ intentions and perceptions lie within the interaction loop remains opaque. To investigate animals’ perceptions and intentions (their level of understanding), scientists have focused on what we can actually measure, by regarding an animal’s senses in terms of the distinct sensory modes available – sound (hearing), light (vision), and chemicals (smell and taste) – and considering the animal’s response to associated stimuli [8]. Because trying to ascertain animals’ level of understanding is complex for humans, with a different umwelt, we focus on measuring and assessing intentionality rather than on attempting to make sense of an animal’s perception of the world.

The problem of understanding umwelt and intentionality is compounded in our context of multiple individuals and species using the same device. Animal species, genera, families, etc. differ markedly from each other, quite possibly occupying various points along a spectrum of understanding [49] and with diverse umwelt experiences. The differences we uncovered between the members of the lemur group in ways of interacting with audio-enrichment devices and using space brought us back to the need to consider how interactive devices could, by catering to the needs of distinct individuals living together, dovetail with the individuals’ or species’ level of understanding. A related significant question involves what aspect of the device should be adjusted for the individuals and, thereby, enable the device to adapt to specific needs. Deeper reflection on intentionality leads to a profound question: how much of the devices’ method and interaction paradigm should rely on how we understand how another species understands the world?

Addressing the intricate interplay of umwelt and intentionality in a multi-species context is indeed a grand challenge. Nonetheless, we must embark on a broader exploration of trends and commonalities across species, genera, families, etc., ultimately cultivating a more nuanced understanding of collaborative design that can accommodate the unique cognitive perspectives of animals and humans in all their variety.

8.3 From HCI to ACI

Finally, the differences displayed by the unique group members in our study further emphasise the need for design that prioritises individuals’ needs over attempts to create a one-size-fits-all solution. Audio devices for animals traditionally have been designed for very small groups of animals, with a single device targeted at the entire group’s needs [24]. We argue that this might not benefit any individual animal sufficiently; therefore, we recommend future devices that accommodate individuals within heterogeneous groups. Fortunately, what many would regard as the ‘first wave’ of HCI has sharpened the focus on ways to understand, develop, and assess systems that adapt to meet individuals’ needs [80]. While systems that adapt are designed to change to support user-specific interaction and information content [47, 80], this is more complicated for designers who work with animals: it is far from easy to address these unique needs when multiple animals have access to the device. The umwelt of a particular species and individual, which informs the understanding of computer interfaces [42], forms one factor here. One way to extend our research is to find ways for the computer to recognise and respond to each individual approaching the device. This should afford more active customising of the audio experience, for example.

It is our fervent hope that the ACI discipline will mirror HCI by rising to meet the above-mentioned first wave – with its adoption of objective measurements angled toward seeing animals as group members and individuals. While most systems have focused on ease of use, as assessed objectively [32], we recommend treating animals as more than the register of an object. The animal, with its agency, is an individual in its own right. Reflecting on our research, we propose that lemurs, much as humans do, have various external factors that influence their use of interactive computer systems. Among these are the social structure and other factors that extend beyond the animals themselves, such as how humans manage them. Our data have revealed that animal computing faces a challenge similar to early HCI efforts, wherein the scope for interpretation and explanation of data was limited. As we struggle to identify the reasons underlying how lemurs engage with audio devices, it is pivotal to acknowledge the risk of anthropomorphising when examining the animals’ computer-related behaviour. This risk is particularly high when approaching animal–computer interaction from the perspective of the HCI field, which has a rich history of influence over ACI. Projects in zoo settings can mitigate this bias by positioning animals as collaborators in the design process – letting them ‘tell us’ how they perceive a new device through their behavioural responses. In short, the dawn of a new era of animal–computer systems may be at hand, if we can shift toward the design of genuinely personalised, adaptive systems.
9 FUTURE WORK

While adding valuable findings and rigour to research into primates’ audio preferences, our study still was necessarily limited to its time, place, and context. Furthermore, incorporating qualitative data into such work would help build a more holistic understanding of the results. In addition, the data-collection difficulties due to similarities among individuals in enclosure 2 (animals of similar ages and the same species) emphasize the need to consider this obstacle before undertaking further work in this regard. We encourage greater effort in collecting individual-level data when possible and studying audio preferences with other primate species on this level. Lastly, while there were sound methodological reasons for not introducing our device in the baseline setting, we acknowledge the possible effects of this factor, since it is impossible to disentangle the device’s features (shape, materiality, provision of shelter, etc.) from the stimuli provided.

10 CONCLUSION

Our study, responding to the increasing use of audio stimuli as enrichment for zoo-housed primates, investigated for the first time how lemurs trigger audio. Its second valuable contribution consists of the interactive audio device itself, adapted for testing with 14 lemurs of three species. Thirdly, while we can articulate findings that the lemurs interacted with LemurLounge significantly more when it played audio as opposed to silence and that they did not demonstrate a preference for any particular audio, variations among species and individuals may be more telling. For instance, age was a factor in how frequently and for how long a lemur used the interaction space, even after the device was removed, and comparing this system to a nearly identical one deployed with white-faced saki monkeys pinpointed considerable differences between primate families in their responses to audio. The extensive variation evident across species, groups, and other boundaries attests to a pressing need for interface designs that suit each cohabiting individual and species. These findings all have extensive implications for the future of interactive computers, which the animal–computer interaction discipline can advance by drawing on the rich history of HCI. Our work, promoting the next wave of development for interactive computer systems for animals, points to parallels with early research within the HCI domain, which we suggest holds parallels with ACI and HCI in painting a comprehensive picture of how individual animals use computers, whereby researchers can align ACI and HCI in understanding the possible implications for the treatment of animals in behavioural research and teaching.

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REFERENCES


