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ZooWear: Animal-Inspired Head-Mounted Haptic Interfaces to Augment the Zoo Experience

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ABSTRACT

Zoos play a crucial role in public education and wildlife engagement, yet traditional visits often lack interactive elements that foster meaningful connections between visitors and animals. In this paper, we introduce ZooWear, a head-mounted wearable featuring cartoon-style animal ears that provides haptic feedback patterns simulating an animal's reactions to other species in the food chain. With ZooWear, we focused on examining its effectiveness in affording perspective-taking during human-animal encounters, promoting embodied knowledge retention, and enriching the zoo experiences. We first conducted a between-subject experiment in lab-based virtual zoo visits to evaluate its effectiveness in creating effective learning experiences and enhancing connections to wildlife. This was followed by a real-world zoo experiment, which showed that ZooWear promoted nature connectedness and enabled more emotionally and socially engaging experiences. Our findings highlight the potential of integrating perspective-taking into zoo experiences through animal-inspired wearables, embodied sensory feedback, and narrative-driven experiences.

KEYWORDS

Human-nature interaction; wearable device; animal-inspired design; haptic feedback; perspective-taking

1. Introduction

Establishing a meaningful connection with nature is increasingly recognized as essential for both human well-being and the promotion of pro-environmental behaviors (Sandifer et al., 2015). However, for people who live in a big city with a busy lifestyle, engaging with nature is becoming rarer (Liu et al., 2018). This detachment can have far-reaching consequences, not only for individual mental and physical health but also for the broader goal of fostering environmental stewardship (Keniger et al., 2013). In urban areas, where access to natural environments is often limited, zoos offer a unique and valuable place for public engagement with nature and wildlife (Curtin, 2009; Godinez & Fernandez, 2019). Zoos allow visitors to observe and learn about various animal species, sparking curiosity and enhancing environmental awareness (Whitehouse et al., 2014). Yet, despite their potential values, zoo experiences in their current format tend to be primarily for appreciation, which makes it hard to develop interspecies connections with wildlife (Greenwell et al., 2023). Visitors often become passive observers with limited opportunities for meaningful interaction, which diminishes both the educational value of the visit and the emotional connections with animals (Orams, 2002).

To address these challenges, researchers in the field of Human-Computer Interaction (HCI) have increasingly explored the use of interactive technologies to enhance visitor engagement in zoos (Syiem et al., 2024). While many existing efforts have concentrated on human-centered observations and interpretations of animal behaviors, recent shifts in the HCI community toward more experimental and de-anthropocentric methodologies have opened new possibilities (Liu et al., 2018; Webber et al., 2020). One promising approach involves fostering perspective-taking, the ability to perceive and consider the

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world from another being's point of view (Batson et al., 1997). In the context of human-nature interactions, this entails shifting away from anthropocentric paradigms to adopt the sensory and ecological perspectives of animals, plants, and other non-human species. By immersing people in the sensory worlds, habitats, and challenges faced by wildlife, perspective-taking can cultivate deeper empathy and connection (Hsu et al., 2024; Hu et al., 2024; Sandbhor et al., 2021; Spangenberger et al., 2022).

In line with this strand, we propose that integrating animal-first perspectives into zoo experiences may transform conventional visits into immersive, sensory-rich interspecies encounters. We introduce ZooWear, a head-mounted wearable device featuring a cartoon-inspired design mimicking animal ears. ZooWear incorporates haptic feedback to simulate various reactions of animals as they interact within their ecological contexts, such as predator-prey dynamics. By enabling users to experience the world from an animal's perspective, ZooWear seeks to transform abstract ecological knowledge into embodied, intimate interactions, enriching zoo visits and fostering interspecies empathy. Our study is guided by the following research questions:

RQ1: How does perspective-taking facilitated by ZooWear enhance visitor experiences, as well as foster understanding and empathy toward wildlife in zoo contexts?

RQ2: What are the opportunities and challenges of integrating perspective-taking into virtual and real-world zoo environments to promote visitor engagement and interspecies interaction?

To answer the above questions, we conducted two experiments in both virtual and real-world zoo settings. The first was a between-subjects experiment with 40 participants in lab-based virtual zoo visits, where one group used ZooWear and the other did not, to compare ZooWear's role in improving user experience, knowledge retention, and nature connectedness. The second experiment involved 16 participants in pairs who wore ZooWear during their visits to the city zoo to assess its influence on the overall visiting experience, connection to nature, and social dynamics among visitors in real-world settings.

The main contributions of our work include:

- We present ZooWear as a practical design exemplar of facilitating perspective-taking in zoo contexts through animal-inspired head-mounted wearable and haptic feedback.
- Through two empirical studies in virtual and real-world zoo settings, we demonstrate the potential of ZooWear to augment visitor experiences and foster empathy and understanding of wildlife.
- Drawing from our findings and reflections, we offer a set of design implications for future integration of perspective-taking into zoo contexts.

2. Related work

2.1. Connection to nature

Reconnection with nature has been a long-standing goal in environmental education and conservation. Research has shown that fostering emotional and cognitive connections with nature can lead to increased environmental stewardship and pro-conservation behaviors (Oliver et al., 2021). In the HCI community, early efforts focused on measuring the positive effects of nature exposure on individuals through self-reports (Wang, 2022), interviews (Saaty et al., 2021), and questionnaires (Salazar et al., 2021). Building on this, recent research has explored using various HCI technologies and designs to improve the connectivity between users and nature (Stepanova et al., 2020). For example, the *Ambient Birdhouse* is an IoT device that displays bird videos on a screen to encourage people's curiosity about local wildlife (Soro et al., 2018). *Closer to Nature* is an interactive installation where elderly users can engage in nurturing animals remotely through tangible interactions (Feng et al., 2018). Besides, there is a growing interest in investigating interactive systems to augment the on-site, embodied experiences with real nature (Cheng et al., 2023). For instance, *My Naturewatch Camera* encourages users to create DIY cameras to capture local wildlife, offering a self-driving way to closely observe and interact with nature (Gaver et al., 2019). *GoChirp* is an AI-powered wearable device that detects bird chirping and provides haptic feedback, thus increasing users' awareness of birds in their surroundings (Li et al., 2025). Additionally, in urban areas with limited access to natural environments, zoos play a vital role in connecting human beings with a

diversity of wild animals. The integration of HCI in zoos shows the potential to enhance visitor engagement and deepen their understanding of wildlife (Greenwell et al., 2023).

2.2. Technology for enhancing the zoo experience

There have been several studies focusing on applying Augmented Reality (AR) technologies in zoo contexts to enhance visitors' interactive experiences with animals (Syiem et al., 2024). These studies are predominantly grounded in the visual modality, adopting a human-centered perspective that provides explicit instructions and thereby facilitates visitors' smooth understanding of animals and their habitats (Srisuphab et al., 2014). For example, Andrade and Shool (2020) developed an augmented reality system that enables participants to watch by wearing augmented reality wearable devices. It uses virtual characters to introduce various species, with an emphasis on their unique traits. Jimenez Pazmino et al. (2013) developed a visualization system for visitors; the challenges faced by polar bears due to global warming are presented through visualizations. Meanwhile, emerging studies have begun to focus on user experience design, exploring multimodal sensory interactions, particularly the auditory modality, to enhance the immersion and engagement of zoo visits. For instance, Pendse et al. developed a sonification system that enabled visitors to learn fish behaviors by mapping the size of fishes and their movements to musical tones and rhythms in the aquarium (Pendse et al., 2008). Similarly, Kleinberger et al. developed a sonic enrichment device that enables parrots to control their interactions with visitors (Kleinberger et al., 2020). To summarize, current zoo technologies generally rely on visual (Syiem et al., 2024) and auditory modalities (Pendse et al., 2008), guiding visitors to observe and understand animals from a human-centered perspective, while relatively little attention has been paid to the haptic modality. Prior research indicates that wearable haptic feedback significantly increases limb embodiment (Frohner et al., 2019). Meanwhile, animal-perspective experiences have been shown to foster empathy (Kasuga et al., 2020). Accordingly, in real-world zoos, wearable devices that integrate haptic interaction with these animal-perspective experiences may further deepen visitors' understanding of animals and strengthen their connection to the natural world.

2.3. Perspective-taking-oriented HNI

The perspective-taking (PT) approach refers to the ability to imagine oneself from another's viewpoint to understand their intentions, motives, or actions (Batson et al., 1997). In the context of human-nature interaction, extensive research has shown that adopting a PT approach can effectively foster empathy and build deeper emotional and cognitive connections with other species. For example, Life on Wings is a board game where players take on the roles of birds, navigating the challenges posed by urbanization (Sandbhor et al., 2021). More recently, research has increasingly underscored the significance of embodied experiences in enabling users to adopt the perspectives of non-human animals. Many studies leverage the affordances of virtual reality (VR), such as its ability to create a sense of presence and embodiment, to achieve this goal (Hu et al., 2024). For instance, AnimalSense immerses users in the sensory worlds of animals, offering insights into how different species perceive their environments through unique sensory modalities (Hsu et al., 2024). Similarly, iStrayPaws provides a first-person journey into the lives of stray animals, confronting users with challenges such as inclement weather, hunger, and illness (Xu et al., 2024). Moreover, an emerging body.

Research has begun to integrate multisensory augmentation to enhance immersion and playfulness, thus catalyzing the PT approach. For example, Spangenberger et al. developed a VR system equipped with tactile and olfactory stimuli, allowing users to embody a tree and reflect on the interconnectedness of natural ecosystems (Spangenberger et al., 2024). Despite these advancements, such efforts remain in their infancy. Additionally, most implementations are confined to virtual or simulated environments. Integrating the PT approach into human-animal encounters in real-world settings presents a promising yet largely unexplored opportunity. Hence, in this article, we explore how the PT approach can be integrated into zoo environments using animal-inspired wearables and haptic feedback to enhance human-animal interactions.

3. ZooWear

As shown in Figure 1, ZooWear is an animal-inspired head-mounted wearable designed to enrich zoo experiences by immersing users in interspecies encounters from an animal's perspective. When wearing ZooWear, users can step into the perspective of a specific animal, such as a fox or a rabbit. As they explore the zoo and approach different animals, ZooWear activates corresponding responses, including ear movements and haptic feedback in various patterns to simulate the animal's reactions to other species in the food chain.

3.1. Design rationale

In this section, we first present the design of ZooWear as a wearable device, followed by an explanation of the tangible ear movements and haptic feedback features.

3.1.1. The wearable design

As shown in Figure 2, the design of ZooWear incorporates cartoon-style, animal-ear-shaped headbands, chosen based on three key considerations. First, the ear-shaped design is both intuitive and playful, immediately evoking an animal's perspective and thereby enhancing user engagement. Second, the headbands are lightweight and comfortable, making them ideal for long-period wear without causing discomfort. Lastly, ear-shaped headbands are socially acceptable for most zoo visitors in different cultures, as seen in theme parks like Disney.

3.1.2. The movement of tangible ears

ZooWear draws inspiration from natural animal behaviors, using ear movements as immediate and visible feedback when encountering other animals. Hearing is crucial for many species in interpreting environmental stimuli and communicating (Heffner, 2004). For instance, grey foxes flatten their ears to signal fear in response to unfamiliar stimuli (Schenkel, 1967). ZooWear mimics these behaviors, with its ears rotating in distinct patterns to signify different interrelationships: When encountering prey, the ears perform four large, deliberate rotations, simulating the vigilance and readiness of a predator

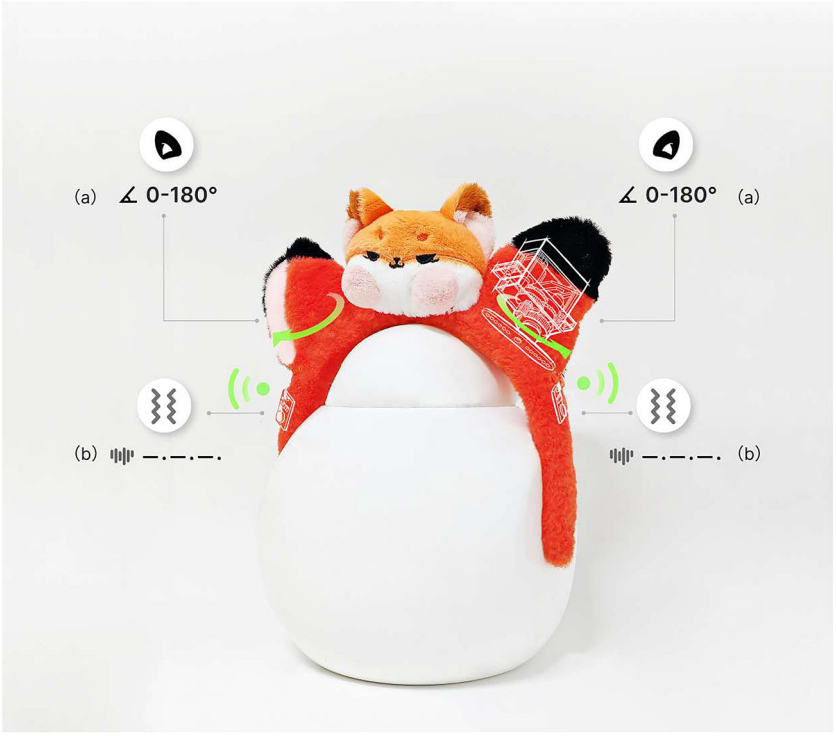

Figure 1. ZooWear Can trigger (a) ear movements and (b) specific patterns of haptic vibrations when users approach different animals.

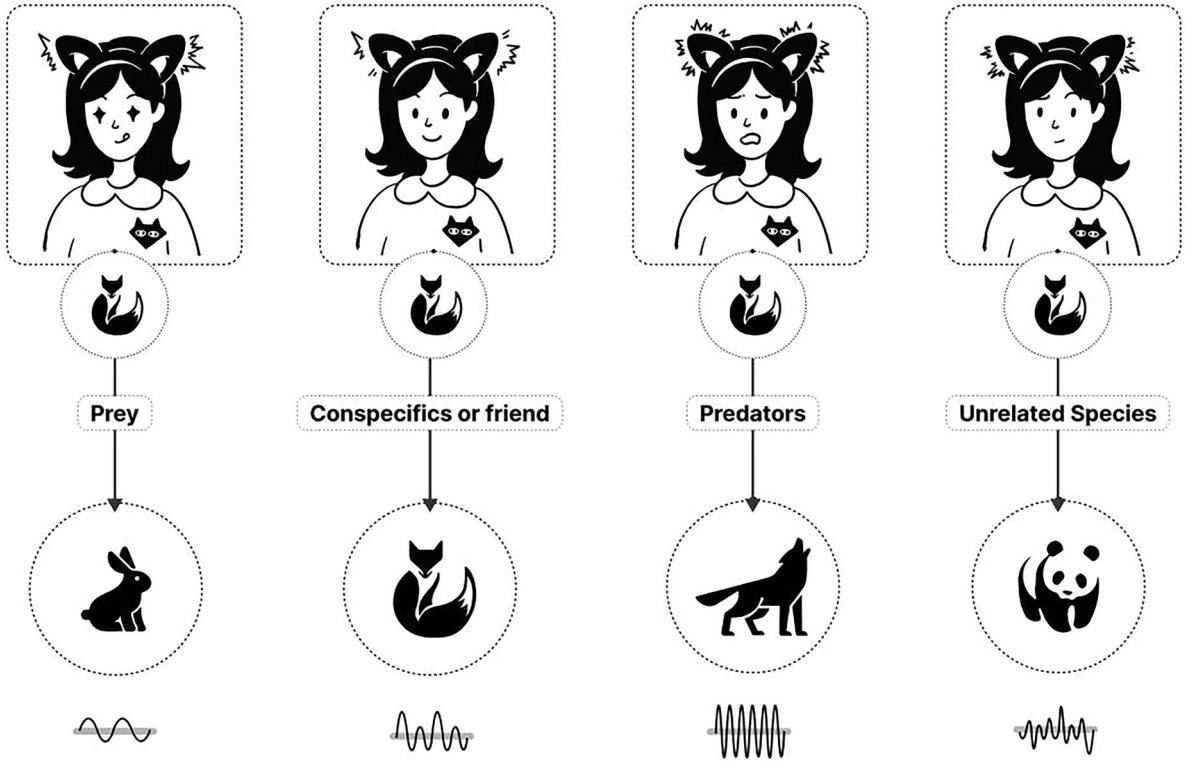

Figure 2. Four different types of ZooWear responses are presented, taking the fox version of ZooWear as an example, which reacts differently when encountering rabbits (prey), foxes (conspecifics), wolves (predators), and pandas (non-specifics).

preparing to hunt. When encountering predators, the ears execute four quick rotations, reflecting heightened alertness and urgency, similar to an animal sensing imminent danger. When encountering unrelated species, the ears perform a single, rapid rotation, symbolizing curiosity and cautious observation of unfamiliar entities. When encountering conspecifics or friends, the ears alternate between fast and slow rotations, conveying liveliness and social bonding typical of encounters among members of the same species. Details of the ear movements are summarized in Table 1.

3.1.3. The haptic feedback

Following ear movements, ZooWear activates different vibration patterns to further enhance feedback when encountering various animals. We encode the interrelationships between the animal the user embodies (fox or rabbit) and the animals they encounter in the zoo into different vibration patterns based on the following three considerations. First, in noisy zoo environments, haptic feedback provides a direct, perceivable signal through the body's mechanoreceptors (Raisamo et al., 2022). Second, vibrations evoke affective responses, deepening emotional engagement and immersion (Katsuno & White, 2021). Third, varying the vibration parameters encodes specific information, allowing users to interpret distinct messages (Dalsgaard, 2022). Describing haptic experiences in terms of rhythm and tempo is a more user-friendly approach (O'Sullivan & Chang, 2006), and these parameters are often mapped onto specific emotional states. For example, faster vibration rhythms are typically perceived as conveying greater intensity (Ferguson et al., 2018); intense, sustained, and rapid haptic patterns are likely to evoke anxiety (Jang & Lee, 2025); in contrast, slow heartbeat-like vibrations can help maintain calmness and focus (T. Azevedo et al., 2017). Aligned with the ear movement design, the specific vibration patterns, based on heuristic assumptions, are designed to correspond to different types of animal encounters: when encountering prey, ZooWear delivers four prolonged vibrations intended to elicit a focused state; when encountering predators, it triggers four rapid vibrations to evoke a sense of tension; for unrelated species, no vibrations are triggered; and when encountering conspecifics or friends, alternating long and short vibrations are triggered. Details of the haptic feedback are summarized in Table 1.

Table 1. Details about the ear movement and haptic feedback.

An example of a column heading	Ear movement	Haptic feedback	Pattern
Encounter 'Prey'	The servo moves back and forth 4 times, each with an angle of 150 degrees, lasting about 0.5 s each, with an interval of 1 s.	Four vibrations, each lasting 1.5 s with an interval of 1 s.	— — — —
Encounter 'Predators'	The servo moves back and forth 4 times, each with an angle of 30 degrees, lasting about 0.2 s each, with an interval of 1 s.	Four vibrations, each lasting 0.5 s with an interval of 1 s.	- - - -
Encounter 'Unrelated Species'	The servo moves back and forth 1 time, with an angle of 30 degrees, lasting about 0.2 s.	No vibration.	
Encounter 'Conspecifics or Friends'	The servo alternates between large and small movements 6 times, with large movements of 150 degrees for about 0.5 s and small movements of 30 degrees for about 0.2 s.	Six alternating vibrations, with long vibrations lasting 1.5 s, with an interval of 1 s and short vibrations lasting 0.5 s, with an interval of 1 s.	— - — - — -

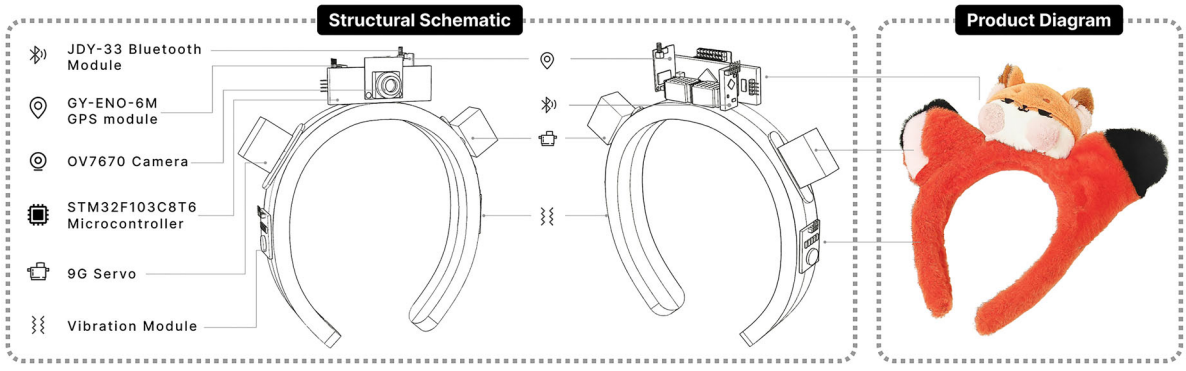

Figure 3. Technical implementation of ZooWear.

3.2. Implementation

Figure 3 shows the technical implementation of ZooWear, which consists of a microcontroller, a Bluetooth module, a GPS module, a camera, a pair of servo motors, and a pair of vibration modules. The STM32F103C8T6 is employed as the core microcontroller, along with a JDY − 33 Bluetooth module to establish communication with the computer. For input, a camera is used to capture images of animals, which are then transmitted to the computer for species identification. However, the effectiveness of visual recognition might be constrained by animal camouflage as well as environmental features in zoos, such as trees and fences. Furthermore, since visitors lack the auditory and olfactory cues that animals employ in the wild (Cartmill, 2023), a GPS module is utilized to detect the user's location and determine proximity to specific exhibits. Based on the identified species, commands are sent to ZooWear to trigger appropriate feedback responses. On the output side, 9 G servos are employed to generate various ear movements. Additionally, a vibration module is implemented to provide haptic feedback, with different haptic effects achieved by varying the duration and repetition of vibrations.

3.3. Study overview on ZooWear's evaluation

As shown in Figure 4, to understand the values and applicability of ZooWear in potential usage settings, two types of experiments were designed and conducted with different setups to systematically examine the effectiveness and underlying mechanisms of the design in both the virtual zoo visit for remote education and the real-world zoo visit for nature relatedness and social interactions. Specifically, study one was carried out in a lab-based virtual visit setting to evaluate ZooWear's

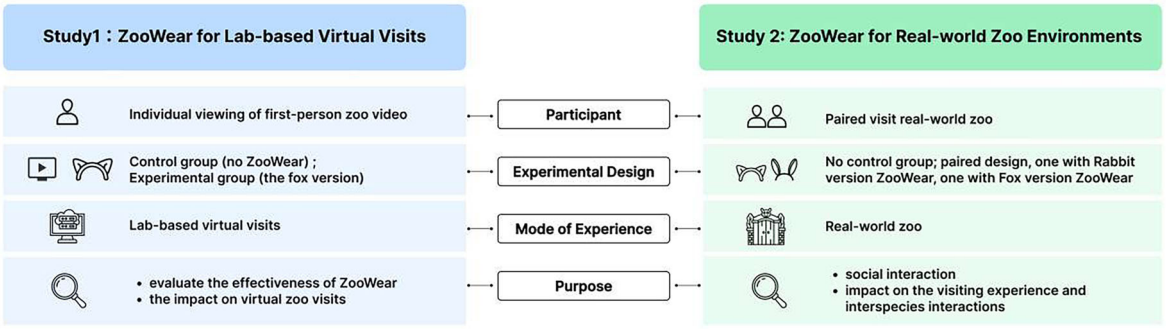

Figure 4. Study overview.

effectiveness in enhancing immersive visit experiences and facilitating knowledge acquisition through perspective-taking from an animal's viewpoint. Regarding study two, the experiment was conducted in a real zoo environment, where a paired zoo visit between two friends was settled, and each of them wore a ZooWear device. Here, we focused on investigating how ZooWear influences real-world zoo visit experiences and the social interactions during the visit.

In the following sections, we describe the experiment designs and research findings of the aforementioned two studies.

4. Study 1: ZooWear for lab-based virtual visits

We first conducted a between-subjects experiment using first-person zoo tour videos to evaluate the effectiveness of ZooWear in virtual zoo visits. Participants were randomly assigned to either a control group that only watched the videos without wearing ZooWear or an experimental group wearing ZooWear. The study design was reviewed and approved by the ethics committee at Beijing Institute of Technology (Reference: BIT-EC-H-2024002).

4.1. Study design

4.1.1. Hypotheses

Our evaluation aimed to test the following three hypotheses:

- H1: Participants using ZooWear will experience more positive emotion than those in the control group.
- H2: Participants using ZooWear will demonstrate greater learning performance than those in the control group.
- H3: Participants using ZooWear will exhibit higher levels of nature-relatedness than those in the control group.

4.1.2. Participants

The experiment involved 40 participants, recruited through word-of-mouth. Each participant received a gift worth approximately 8 CNY ($\approx$ 1 USD) as compensation. All participants were provided with clear, comprehensive information regarding the experiment's objectives, anonymization procedures, and data usage policies. After excluding invalid data, 39 valid samples remained for further analysis: 20 participants (7 males, 13 females) in the control group and 19 participants (8 males, 11 females) in the experimental group. The mean age was 23.85 years (SD = 0.85) for the control group and 22.95 years (SD = 2.72) for the experimental group.

4.1.3. Setup

A first-person zoo tour video, approximately 7 min in length, was displayed on a 27″ LCD monitor. The video featured a sequence of animals, including a zebra, eagle, wolf, fox, badger, meerkat, pheasant, elephant, marmot, and lynx. In the control condition (see Figure 5(a)), participants did not wear

Figure 5. The experimental setting for lab-based virtual visits: (a) the control group watches the zoo tour videos without ZooWear; (b) the experimental group watches zoo tour videos while wearing ZooWear; (c) "wizard-of-Oz" approach.

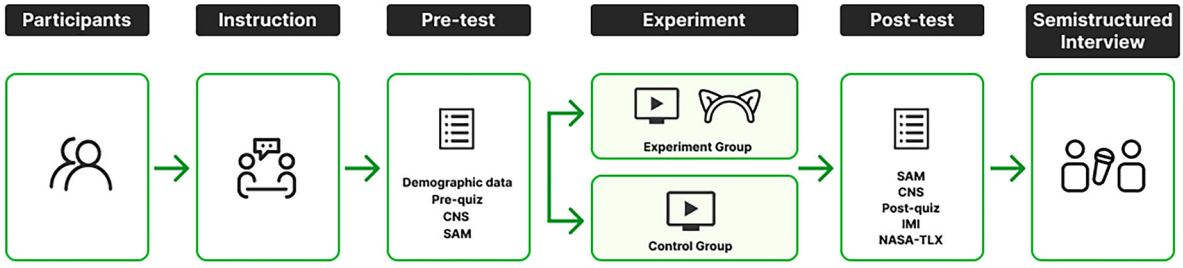

Figure 6. The overview of experimental procedures in lab-based virtual visits. CNS = Connectedness to nature Scale; SAM = Self-assessment manikin; IMI = Intrinsic motivation questionnaire; NASA-TLX = NASA Task Load Index.

ZooWear. In the experimental condition (see Figure 5(b)), participants wore the fox version of ZooWear. As animals appeared in the video, ZooWear provided corresponding ear movements and haptic feedback based on the fox's relationship with each encountered animal.

To enhance the prototype's reliability and stability, we employed a "Wizard-of-Oz" approach (Asaf et al., 2021), replacing the camera recognition system with Bluetooth communication via a smartphone. As shown in Figure 5(c), when participants encountered different animals, the researcher would send commands from the phone to ZooWear, triggering the appropriate feedback.

4.1.4. Procedure

Figure 6 presents the overview of experimental procedures. Researchers first introduced the processes and tasks during the experiment. Also, participants in the experimental group experienced different vibration patterns and received instructions on the meaning of each pattern. Afterward, participants filled in a demographic information form, including details about their gender identity, age, and major, and then completed the pre-quiz, CNS, and SAM. Then, participants began to experience virtual zoo visits. Throughout the study in the experimental group, one researcher monitored the participants' screens and sent signals to activate ZooWear in real time using the phone. Upon task completion, participants filled out SAM, NASA-TLX, post-quiz, CNS, and IMI. Finally, a semi-structured interview was conducted. All interviews were recorded and transcribed for analysis.

4.1.5. Data collection

Before and after the experiment, participants completed a series of questionnaires to assess their experience, learning performance, and perceived connectedness to nature. Both quantitative and qualitative data were collected to test the three hypotheses.

First, the evaluation of user experience mainly focuses on the emotional state and intrinsic motivation. Emotional states were measured using the Self-Assessment Manikin (SAM), focusing on *arousal* and *valence*, with ratings on a 9-point scale (Bradley & Lang, 1994). Intrinsic motivation was assessed using two subscales of the Intrinsic Motivation Inventory (IMI)—*interest/enjoyment* and *relatedness*—adapted for our study (McAuley et al., 1989). Responses were rated on a 7-point Likert scale (see Appendix A1).

Second, participants' learning performance was measured through pre- and post-tests, consisting of a quiz on food chain relationships. Participants answered 10 closed-ended questions, such as *"In the food chain, is the wolf the prey, predator, unrelated, or conspecific to the fox?"* (See Appendix A2)." The correct answer rate was calculated. We hypothesized that participants using ZooWear would be able to understand the meanings of different haptic patterns and use them to determine food chain relationships between the animals they encountered and the fox. Additionally, to evaluate whether the learning process introduced extra workload, we used the NASA Task Load Index (NASA-TLX), which measures perceived workload across six dimensions: *mental demand, physical demand, temporal demand, performance, effort, and frustration*, with ratings on a 20-point scale (Hart & Staveland, 1988).

Third, participants' nature-relatedness was assessed using the Connectedness to Nature Scale (CNS) (Mayer & Frantz, 2004). The questions were adapted to suit the context of the study, with responses rated on a 7-point Likert scale (see Appendix A3).

Finally, semi-structured interviews were conducted with each participant in the experimental group, lasting approximately 20 min. The topics of the interview were as follows: (i) their past zoo visits and motivations; (ii) their overall impressions of ZooWear; (iii) their understanding and interpretation of the haptic feedback; (iv) suggestions for improving ZooWear and expectations for future iterations in real-world zoo settings.

4.1.6. Data analysis

We used SPSS software to analyze the quantitative data. For SAM data, we conducted non-parametric paired Wilcoxon tests to assess changes in participants' arousal and valence before and after the study. For IMI, we calculated the mean of the items within each of the two dimensions. We then conducted independent t-tests to compare these dimensions between the groups.

For the quizzes, we conducted a paired t-test to assess improvements in participants' accuracy after the study. Additionally, an independent t-test was employed for between-group comparisons before and after the experiment. For NASA-TLX, we calculated the mean score across all items, following the same statistical procedure as used for the IMI analysis to compare each item between the control and experimental groups.

For CNS, we employed the same statistical procedure as used for quiz analysis to assess improvements after the study and between-group comparisons.

For qualitative analysis, all interview transcripts were imported into MAXQDA 2022 software for thematic analysis using a bottom-up approach (Braun & Clarke, 2006). One author finished the first round of open coding. Two authors then administered the selective coding process to elicit the interpretation of quantitative data, factors that were perceived to augment the virtual zoo experience, and opportunities associated with the iteration of ZooWear.

4.2. Results

In this section, we present both the quantitative and qualitative results from lab-based virtual zoo experiments.

4.2.1. Quantitative results

H1: Virtual zoo visits with ZooWear were more enjoyable.

Figure 7 illustrates the Self-Assessment Manikin (SAM) results. For *arousal*, in the control group, no significant differences were found between pre- and post-experiment scores (pre: $M = 4.95$, $SD = 2.04$; post: $M = 5.75$, $SD = 1.94$). In the experimental group, there was a significant increase in arousal scores from pre-experiment ($M = 4.53$, $SD = 1.95$) to post-experiment ($M = 6.63$, $SD = 1.61$), with $p < 0.05$. Similarly, for *valence*, no significant changes were observed in the control group (pre: $M = 6.05$, $SD = 2.24$; post: $M = 6.30$, $SD = 1.98$), but the experimental group showed a significant improvement from pre-experiment ($M = 5.47$, $SD = 1.95$) to post-experiment ($M = 7.00$, $SD = 1.45$), with $p < 0.05$.

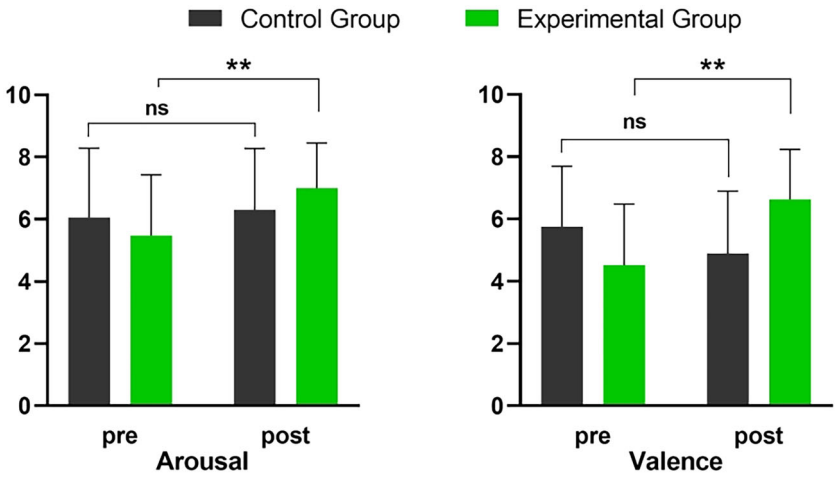

Figure 7. The results of the Self-Assessment manikin (SAM).

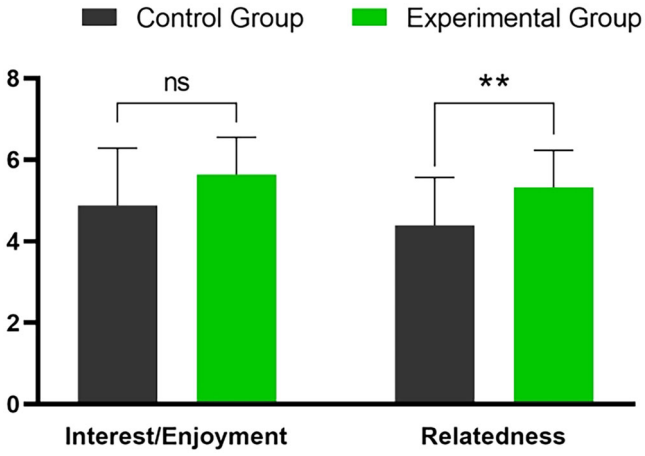

Figure 8. The results of the intrinsic motivation inventory (IMI).

Figure 8 shows the Intrinsic Motivation Inventory (IMI) results. For *interest/enjoyment*, the experimental group (M = 5.64, SD = 0.91) scored higher than the control group (M = 4.88, SD = 1.40), but the difference was not statistically significant ($p > 0.05$). For *relatedness*, the independent samples t-test revealed that the experimental group had a significantly higher mean score (M = 5.32, SD = 0.91) than the control group (M = 4.39, SD = 1.18), with $p < 0.01$.

In summary, the SAM and IMI results support our first hypothesis that participants using ZooWear experience more positive emotions than those in the control group. First, the results of SAM suggest that virtual zoo visits with ZooWear can enhance participants' emotional state of arousal and pleasure. Second, the IMI results demonstrate that ZooWear's interactivity increased participants' intrinsic motivation, especially in terms of relatedness. This suggests that ZooWear enhances the sense of presence in the virtual environment, making participants feel closer to the animals and more inclined to interact with them. These findings indicate that the perspective-taking and physical feedback provided by ZooWear can positively influence users' experiences in virtual zoo settings.

H2: Improved learning performance due to ZooWear

Figure 9 shows participants' learning performance before and after the experiment. In the control group, no significant differences were found between pre- and post-experiment scores (pre: M = 6.05, SD = 1.32; post: M = 5.65, SD = 1.73). In the experimental group, there was a significant increase in scores from pre-experiment (M = 6.26, SD = 1.56) to post-experiment (M = 9.63, SD = 0.76), with $p < 0.05$. For between-group comparisons, there was no statistically significant difference between the two groups before the experiment. However, after the experiment, the experimental group scored significantly higher than the control group, with $p < 0.05$.

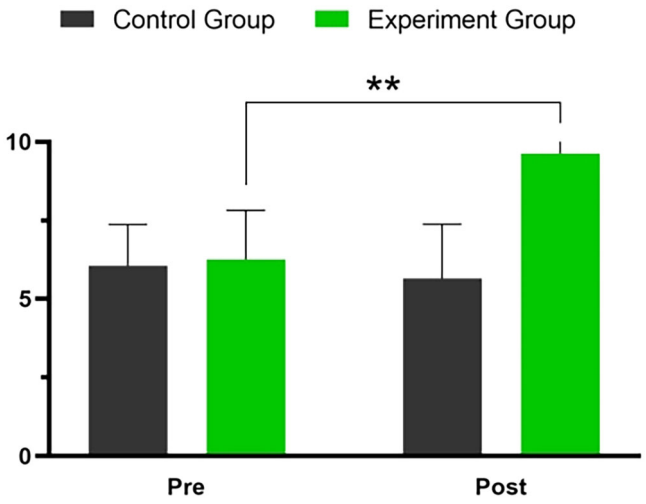

Figure 9. The results of the knowledge quiz.

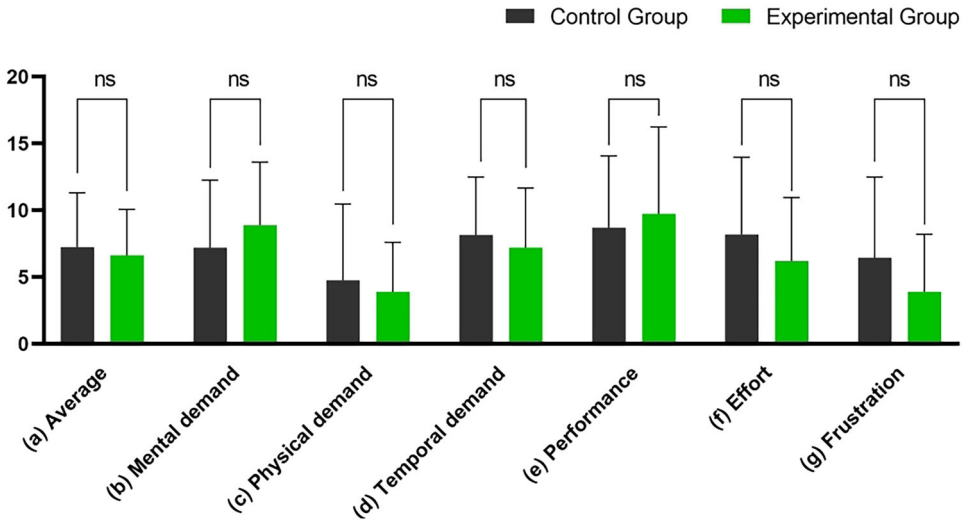

Figure 10. The results of the NASA task load index (NASA-TLX).

Figure 10 illustrates the NASA Task Load Index (NASA-TLX) results. Independent samples t-test revealed no significant differences between the control group and the experimental group in *average* (the experimental group: M = 6.64, SD =3.43; the control group: M = 7.24, SD = 4.06), *mental demand* (the experimental group: M = 8.89, SD =4.71; the control group: M = 7.20, SD = 5.06), *physical demand* (the experimental group: M = 3.90, SD =3.71; the control group: M = 4.75, SD = 5.73), *temporal demand* (the experimental group: M = 7.21, SD =4.47; the control group: M = 8.15, SD = 4.34), *performance* (the experimental group: M = 9.73, SD =6.51; the control group: M = 8.70, SD = 5.37), *effort* (the experimental group: M = 6.21, SD =4.76; the control group: M = 8.20, SD = 5.78), *frustration* (the experimental group: M = 3.90, SD =4.32; the control group: M = 6.50, SD = 6.05).

In summary, the results of the knowledge quiz and NASA-TLX confirmed our second hypothesis that participants using ZooWear demonstrated greater learning performance than those in the control group. The physical feedback—such as ear movements and haptic sensations—appears to function as an embodied interaction, helping participants identify and retain knowledge about the food chain. Additionally, the NASA-TLX results indicate that participants were able to recognize different haptic feedback patterns and interpret the embedded information without experiencing additional workload.

H3: Improved nature relatedness due to ZooWear

Figure 11 illustrates the Connectedness to Nature Scale (CNS) results. In the control group, no significant differences were found between pre- and post-experiment scores (pre: M = 4.87, SD = 0.94;

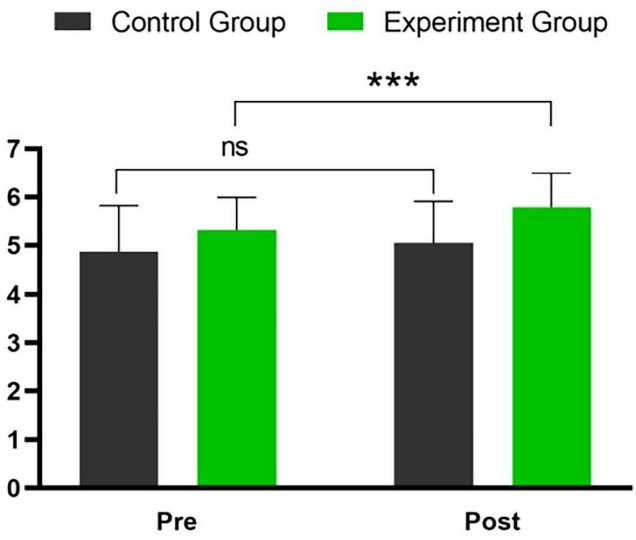

Figure 11. The results of the connectedness to nature Scale (CNS).

post: M = 5.06, SD = 0.84). However, in the experimental group, there was a significant increase from pre-experiment (M = 5.32, SD = 0.67) to post-experiment (M = 5.79, SD = 0.70), with $p < 0.001$. For between-group comparisons, no statistically significant difference was found between the two groups before the experiment. After the experiment, the experimental group scored significantly higher than the control group, with $p < 0.05$.

In summary, the results of the CNS confirmed our third hypothesis that participants using ZooWear exhibited higher levels of nature relatedness than those in the control group. By engaging with the virtual environment from the perspective of an animal, participants were able to develop a deeper sense of empathy and closeness to the wildlife they encountered. These findings suggest that the interactivity of ZooWear can effectively enhance nature relatedness, potentially influencing participants' attitudes toward wildlife and conservation efforts.

4.2.2. Qualitative results

In this section, we present the qualitative results to complement the quantitative data, highlighting factors that participants perceived as enhancing their virtual zoo experience, as well as opportunities for iterating ZooWear in virtual settings.

4.2.2.1. Enhanced animal understanding through shifted viewpoints. When encountering animals, they found themselves unconsciously adopting the animal's perspective, leading to a shift in viewpoint. For example, one participant remarked, "*Before, I just thought of tigers as fierce. But after wearing ZooWear, I couldn't help but see them as powerful predators—it gave me this intense urge to run!*" (P8) Many participants noted that traditional animal education often uses anthropomorphic, cartoonish, or overly simplistic representations. In contrast, this unique perspective shift enabled by ZooWear facilitated a more in-depth and multifaceted understanding, such as "*I used to think of foxes only in terms of their roles in 'Zootopia,' but ZooWear made me realize that foxes are predators in the food chain, either being hunted or cunningly hunting other animals.*" (P2)

4.2.2.2. Information representation and emotional engagement through haptic cues. During virtual zoo visits, participants were able to distinguish various haptic patterns. As one remarked, "*The haptic signals from ZooWear were attention-grabbing, intuitive, and memorable.*" (P6) Beyond conveying objective information, ZooWear's haptic feedback enhanced emotional connections to the animals encountered. ZooWear could enrich their sensory experience in a virtual zoo visit. The varied vibration patterns elicited a range of emotions, from excitement and curiosity to heightened alertness and even mild fear. One participant remarked, "*When I felt the short, rapid, and intense vibrations triggered by a predator, I experienced genuine anxiety. It gave me a glimpse into what the animal might feel in that*

Figure 12. The two participants are visiting the city zoo together, one wearing the fox version of ZooWear and the other wearing the rabbit version.

moment. The excitement and curiosity I had at the beginning turned into a sense of heightened alertness, and then a tinge of mild fear crept in." (P11) This emotional resonance was frequently highlighted as a key factor in making the experience both immersive and memorable.

4.2.2.3. Expectations for enhanced social interactivity. Given that most zoo visits are shared experiences with friends and family, many participants suggested developing a multi-user version of ZooWear to enable social interaction among users, thereby enhancing the collective enjoyment of the experience. For example, users could share discoveries in the virtual environment, explore together, or collaborate on tasks, which would increase social fun. One participant explained, *"I'd love to go on a virtual Antarctic expedition with my friends, watching penguins huddle together to stay warm while we share our findings in real-time."* (P4) This type of shared experience, participants noted, would encourage discussion, allowing users to exchange thoughts on different animals, leading to a richer educational experience.

4.2.2.4. Desire for more imaginative narratives and scenarios. Participants recognized that one of the key advantages of virtual zoo visits is the ability to present environments and scenarios that are impossible to experience in real life. They suggested that ZooWear could incorporate more rare and extreme situations to push the boundaries of everyday experiences. For instance, one participant mentioned, *"I'd love to be transported to a prehistoric world where I could observe dinosaurs in their natural habitat or experience the harsh Arctic winds while watching polar bears hunt for seals."* (P17) Simulating the habitats of extinct species, recreating ancient ecosystems, or observing animal behavior under extreme weather conditions would offer more intense, thought-provoking experiences. Participants agreed that these highly immersive and imaginative scenarios would help them develop a broader and deeper understanding of the diversity and complexity of animal life.

5. Study 2: ZooWear for real-world zoo environments

We conducted a within-subjects experiment to evaluate ZooWear's effectiveness in real-world zoo visits. In addition to assessing ZooWear's impact on the visiting experience and interspecies interactions, we also considered the social dynamics inherent in real-world zoo environments. Therefore, we were interested in how ZooWear might influence social interactions during zoo visits. To explore this, participants wore ZooWear with different animal roles and participated in the experiment in pairs (see Figure 12). The study design was reviewed and approved by the ethics committee at Beijing Institute of Technology (Reference: BIT-EC-H-2024002).

5.1. Study design

5.1.1. Hypotheses

Our evaluation of ZooWear aimed to test the following two hypotheses:

- H1: With ZooWear, participants will demonstrate increased motivation for the zoo visit.
- H2: With ZooWear, participants will exhibit higher levels of nature relatedness after the zoo visit.

5.1.2. Setup

As shown in Figure 13, we provided two animal-themed versions of ZooWear: fox and rabbit. The experiment was conducted at City Zoo, where we designed a pre-selected route to ensure participants encountered a wide variety of animals. The tour lasted approximately 45 min, during which participants visited the following exhibits in sequence: the Giant Panda Pavilion, the Pheasant Garden (featuring parrots, hornbills, golden pheasants, snow pheasants, and long-tailed pheasants), the Small Mammal Area (featuring raccoons, guinea pigs, and masked palm civets), the Tropical Monkey Area (featuring ring-tailed lemurs, red-tailed monkeys, and gray bamboo lemurs), the Small Carnivore Area (featuring silver and red foxes), the Lion and Tiger Area, the Australian Pavilion (featuring kangaroos and emus), and the Elephant Area.

To ensure the prototype's reliability and stability, we employed a "Wizard-of-Oz" methodology (Asaf et al., 2021). During the experiment, two researchers accompanied the participants, controlling the two ZooWear devices without causing any disruption. When participants encountered an animal, the researchers would send commands via phone to ZooWear, triggering the appropriate feedback.

5.1.3. Participants

The experiment involved 8 pairs of participants, totaling 16 individuals (4 males, 12 females), aged 22 to 26 (M = 23.56, SD = 0.96). Each pair of participants was preexisting and familiar with each other before the experiment. Participants were recruited through personal networks. As compensation, each participant received a zoo ticket valued at approximately 15 CNY and a gift worth 8 CNY (totaling around 3.2 USD). Participants were fully informed about the experiment's purpose, anonymization procedures, and data usage policies.

5.1.4. Procedure

Figure 14 provides an overview of the experimental procedures. Researchers first introduced the experiment's processes and tasks. Participants selected the animal role and wore ZooWear. They experienced vibration patterns with instructions to ensure they could interpret the haptic feedback for different animals. They then filled out a demographic information form, including details on gender identity, age,

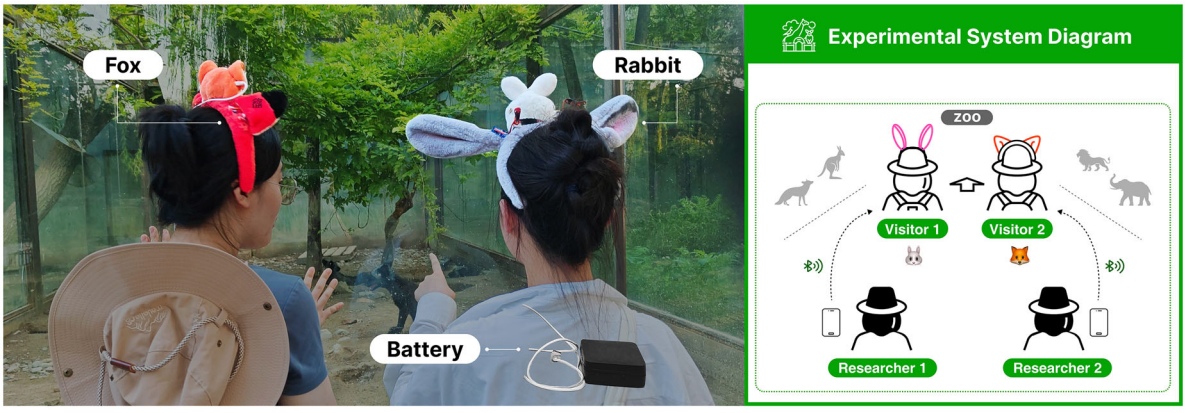

Figure 13. ZooWear—The fox version and the rabbit version of ZooWear are displayed, both connected to battery power.

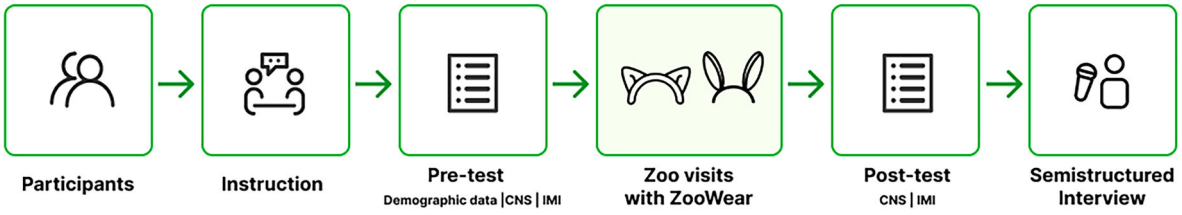

Figure 14. The overview of experimental procedures in real-world environments. CNS = Connectedness to nature Scale; IMI = Intrinsic motivation questionnaire.

and major, followed by the completion of the CNS and IMI scales. Next, participants began the zoo tour accompanied by two researchers, sending signals via phone to activate ZooWear in real time. Upon completion of the tour, participants filled out the CNS and IMI scales again. Finally, a semi-structured interview was conducted online. All interviews were audio-recorded for further data analysis.

5.1.5. Data collection

To test the first hypothesis, we used two subscales from the Intrinsic Motivation Inventory (IMI)—*interest/enjoyment* and *relatedness*—to evaluate participants' motivation for zoo visits before and after the experiment (McAuley et al., 1989). The terms in the scale were adapted to fit our context, with responses rated on a 7-point Likert scale.

To test the second hypothesis, we used the Connectedness to Nature Scale (CNS) to assess participants' nature relatedness before and after the experiment (Mayer & Frantz, 2004).

Additionally, we conducted a semi-structured interview lasting approximately 30 min per participant to gain a more in-depth understanding of participants' thoughts and experiences. The topics included (i) their previous zoo visits and motivations; (ii) their overall impressions of ZooWear and interpretation of the different feedback; (iii) social interaction with their paired participant; and (iv) their thoughts and expectations for ZooWear's iteration and enhancing interactivity in the zoo experience.

5.1.6. Data analysis

For quantitative analysis, we used SPSS software to analyze the CNS and IMI data, calculating the mean scores and conducting paired t-tests to assess improvements after the study. For qualitative analysis, interview transcripts were imported into MAXQDA 2022 for thematic analysis following a bottom-up approach (Braun & Clarke, 2006). One author conducted the initial round of open coding, after which two authors carried out selective coding to interpret the quantitative findings, identify factors that enhanced the real-world zoo experience, and explore opportunities for iterating ZooWear.

5.2. Results

In this section, we present both the quantitative and qualitative results from a real-world zoo environment study.

5.2.1. Quantitative results

H1: Improved motivation for zoo visits

Figure 15 presents the Intrinsic Motivation Inventory (IMI) results. For *interest/enjoyment*, paired-samples t-tests indicated that scores increased significantly from 5.11 ± 0.76 pre-experiment to

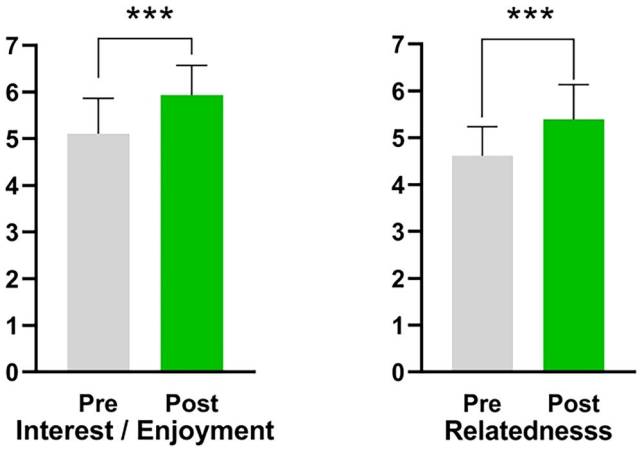

Figure 15. The results of the intrinsic motivation inventory (IMI) subscales of interest/enjoyment and relatedness.

5.94 ± 0.63 post-experiment ($p < 0.001$). For *relatedness*, paired-sample t-tests revealed that scores increased from 4.62 ± 0.62 to 5.39 ± 0.75, also demonstrating a significant improvement ($p < 0.001$).

The IMI results confirmed our first hypothesis that with ZooWear, participants can demonstrate increased motivation for the zoo visit. By integrating animal-first perspectives into the experience, ZooWear transforms conventional visits into immersive interspecies encounters, positively influencing both enjoyment and the sense of relatedness to the animals. This suggests that ZooWear's interactivity fosters greater emotional engagement, enriching the overall zoo experience.

5.2.1.1. Demonstrate increased motivation for the zoo visit with ZooWear.

H2: Improved nature relatedness due to ZooWear

Figure 16 presents the Connectedness to Nature Scale (CNS) results. A paired samples *t*-test revealed a significant improvement in participants' scores from pre-experiment (5.30 ± 0.46) to post-experiment (5.92 ± 0.52), with $p < 0.001$.

The CNS results confirmed our second hypothesis that with ZooWear, participants can exhibit higher levels of nature relatedness after the zoo visit. This improvement suggests that the embodied interaction enabled by ZooWear helps participants engage with animals in a more direct, sensory way. This interaction appears to strengthen participants' emotional connection to the animals and the environment, making them feel more attuned to nature.

5.2.2. Qualitative results

Several key themes emerged from the interviews, highlighting how ZooWear promoted nature engagement, active exploration and reflection, social interaction, and areas for potential improvement in future iterations. Our analysis specifically highlights aspects unique to real-world zoo visits.

5.2.2.1. Promoting nature literacy in situated learning. Nearly all participants recognized ZooWear's ability to enrich their connection with nature and improve the educational value of their zoo visits. Rather than relying on reading signs or watching videos to learn about the animals, ZooWear offered a more engaging and interactive experience for zoo education. As one of the participants explained, *"In traditional zoos, the educational content is usually delivered through static images, videos, or text. But ZooWear transforms this into something much more engaging—it's not only immersive but also intuitive."* (P4) ZooWear seemed to stimulate participants' curiosity about the animals they encountered, sparking discussions and encouraging them to actively engage with the exhibits. Many participants noted that this real-time, haptic feedback made the learning process more engaging, moving beyond passive observation to create participatory learning. These results demonstrate ZooWear's potential to promote situated learning, where knowledge is acquired in a relevant, real-world context, enhancing both understanding and retention.

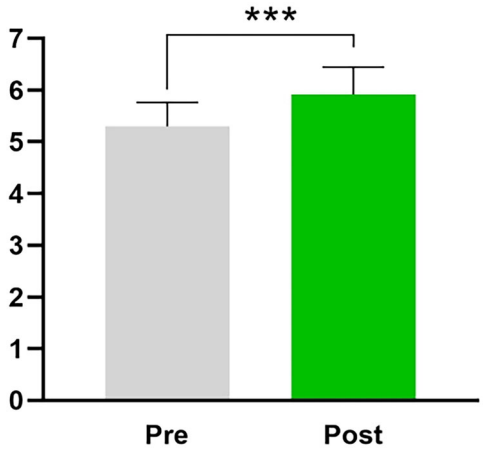

Figure 16. The results of the connectedness to nature Scale (CNS).

5.2.2.2. Digital augmentation encourages active exploration. ZooWear significantly heightened participants' motivation to explore the zoo independently. The wearable device provided continuous haptic feedback that varied depending on the animals the participants encountered, adding a layer of excitement and curiosity to the experience. As one participant described, *"Wearing ZooWear gave me a sense of thrill. I started seeking out prey animals, making me feel like I was in control of my own experience."* (P1) The dynamic between predator and prey in ZooWear added a gamified element to the zoo tour, turning it into a form of interactive storytelling. Participants no longer felt like passive observers; instead, they became active builders in their exploratory narratives.

5.2.2.3. Perspective-taking facilitates empathy and positive reflection. One of the most striking outcomes of the study was the degree to which ZooWear facilitated feelings of empathy toward the animals. Several participants remarked that by embodying the role of an animal through ZooWear, they began to see the animals not just as exhibits, but as beings with lives and environments that deserved closer attention and care. As one participant noted, *"When I visited the fox exhibit, I started thinking of them as my companions, which made me pay more attention to their behavior and surroundings. This made me reflect on whether the zoo environment supports their well-being." (*P12) This kind of role-playing allowed participants to experience a deeper connection to the animals, prompting them to reflect on conservation issues, animal welfare, and their responsibilities toward nature.

5.2.2.4. Peer-based contexts facilitate social interaction. During the zoo visits, we observed that ZooWear engages participants in playful interactions between them. This type of social interaction was particularly evident when participants reacted to each other's feedback patterns and animal-themed experiences. For instance, when participants gathered in front of the fox exhibit, those experiencing the perspective of a fox noticed the ears of participants wearing rabbit-themed ZooWear twitching rapidly. They humorously remarked, *"Haha, you look so nervous, like an alarm going off."* Meanwhile, participants adopting the rabbit's perspective observed those wearing fox-themed ZooWear and commented, *"You look quite relaxed."* In addition, participants frequently compared their haptic feedback, speculating about the biological relationships between the animals represented by their ZooWear. As they walked through various exhibits, they would observe changes in the ear movements of their partner's ZooWear, guessing the nature of the predator-prey relationships. The social nature of this experience suggests that ZooWear has the potential to transform zoo visits into collaborative learning experiences, where groups of visitors can share in the educational journey together, enhancing both individual and collective engagement.

5.2.2.5. Enhancing the immersiveness and clarity of feedback. While ZooWear received positive feedback overall, some participants observed that the haptic feedback's effectiveness was reduced in crowded or noisy environments. As one participant explained, *"When the zoo got busy and loud, it was difficult to focus on the haptic sensations—the feedback seemed to get drowned out by the noise." (*P13) This feedback suggests that future iterations of ZooWear need to address issues related to the clarity and strength of the haptic signals, particularly in environments with high levels of sensory input. Some participants suggested that adding multimodal feedback, such as auditory cues or more distinct vibration patterns, could help mitigate this issue and make the experience more immersive and easier to interpret in distracting environments. For example, one participant proposed, *"When encountering a predator, there could be a strong heartbeat sound as an auditory stimulus, which would create a more intense atmosphere and make the feedback more noticeable."* (P5)

5.2.2.6. Personalized educational content and interactive experiences. Many participants emphasized the importance of tailoring ZooWear to meet the diverse needs of zoo visitors. Since zoos offer both a physical and social environment that attracts different types of users with varying interests and knowledge levels, future iterations of ZooWear should consider how to adapt to these different user profiles. Several participants mentioned that the animal roles could influence the complexity of the content, making it more suitable for specific groups. For instance, one participant remarked, *"As the rabbit,*

which is at the bottom of the food chain, the feedback was relatively simple and predictable. This felt a bit boring for me, but for younger children or those with less knowledge, it might be more appropriate." (P7) In addition to individual preferences, participants highlighted the importance of considering the social dynamics between zoo visitors and the varying expectations they bring. For example, one participant noted, "*Friends visiting the zoo together might be there to have fun and relax, while parents bringing their children would expect the zoo to play a stronger educational role*." (P12) Moreover, preferences for interaction and feedback varied significantly among users. Some participants expressed a desire for more precise, informational content, saying, *"ZooWear could provide specific information through voice prompts, like where a certain exhibit is located or more details about an animal's habits."* (P4) Others favored a more experiential and gamified approach, suggesting, *"ZooWear could incorporate more game-like elements, such as requiring me to find and join up with my animal partner within a set time to avoid being harmed by predators."* (P6) This feedback indicates the need for future designs to balance precise educational content with interactive, gamified experiences that cater to different user groups, ensuring that ZooWear can enhance both the learning and enjoyment of zoo visits across a broad audience.

6. Discussion

As Spors et al. (2023) suggest, perspective-taking from non-human actors in the natural world—engaging with their lives, ways of being, and narratives—is crucial for reconnecting people with nature and fostering empathy. Building on this concept, we propose that integrating animal-first perspectives into zoo experiences can transform traditional visits into immersive, sensory-rich encounters that bridge the gap between humans and wildlife. In this article, we introduce ZooWear, a head-mounted wearable device designed to resemble animal ears in a cartoon style. ZooWear provides haptic feedback in various patterns to simulate an animal's reactions within its ecological context, particularly its interactions with other species in the food chain. With ZooWear, we conducted two types of experiments in virtual and real-world zoo environments, respectively, to assess its effectiveness in facilitating perspective-taking, thereby enhancing the zoo visit experience and fostering interspecies understanding. The first experiment focused on examining the effects of ZooWear in a virtual zoo setting, while the second explored its relationship with social interactions in a real-world zoo context.

In this section, we first present the main findings from two experiments in response to RQ1, followed by a discussion on the design implications of incorporating perspective-taking into both virtual and real-world zoo environments, addressing RQ2.

6.1. Main findings

Our quantitative and qualitative findings demonstrate that adopting an animal's perspective, along with the haptic feedback, significantly enriches the visitor experience, promotes informal learning about ecosystems, and fosters deeper human-wildlife interactions.

First, haptic augmentation has been proven effective in both lab-based and real-world zoo settings. The results from both experiments indicate that visitors can significantly enhance their ability to perceive and interact with the emotional states of animals through haptic feedback. This supplementary haptic modality not only compensates for the limitations of visual experiences but also enhances the social and emotional dimensions of the zoo visit, strengthening the emotional connection between visitors and animals, thereby adding additional interactive value to the overall zoo experience.

Second, the results related to emotional states and intrinsic motivation underscore the value of perspective-taking facilitated by ZooWear in enhancing the zoo experience. By wearing ZooWear, visitors move beyond the passive, visual observation typically associated with traditional zoo visits. Rather than merely viewing animals from a human-centric viewpoint, they engage with them through the lens of predators, prey, or companions. This shift offers a more immersive and empathetic interaction with the animals. Furthermore, ZooWear's haptic feedback enhances this experience by providing sensory augmentation that seamlessly integrates the physical and virtual realms. Through this embodied interaction, visitors adopt the perspectives of different animals, exploring alternative identities and

relationships that are not possible in the real world. This fosters meaningful social interactions as participants compare their experiences of "walking in the shoes" of various animals, leading to shared insights and deeper emotional engagement.

Third, our findings regarding learning performance reveal that ZooWear effectively scaffolds situated learning, an approach that anchors the learning process within the context of the environment itself. This stands in stark contrast to traditional zoo education, where information is typically conveyed through static displays and signage. By offering real-time, context-sensitive feedback, ZooWear facilitates a more dynamic and personalized learning experience. The interactive nature of the device, with features like detecting predator-prey dynamics through ear movements and vibrations, also encourages a playful and socially constructive approach to knowledge. Participants in the zoo experiment reported that ZooWear sparked their curiosity, motivating them to actively seek out specific animals and engage in discussions with fellow visitors about their experiences.

Finally, participants who used ZooWear demonstrated significant increases in empathy and connectedness to nature, as evidenced by notable improvements in their Connectedness to Nature Scale (CNS) scores. One of ZooWear's most profound impacts is its ability to cultivate interspecies empathy. By allowing visitors to experience the world through the eyes of the animals, ZooWear fosters not only a cognitive understanding of their roles within ecosystems but also a deep emotional connection to wildlife. This kind of perspective-taking promotes a holistic, empathetic engagement with nature that transcends traditional zoo experiences.

6.2. Design implications

We first discuss the unique characteristics of both real-world and virtual zoo contexts, emphasizing the different challenges and opportunities each presents. We then explore how animal-inspired wearables, embodied sensory feedback, and narrative-driven experiences can be leveraged to integrate animal perspectives into zoo environments.

6.2.1. Real-world zoos as complex and contextualized environments

Previous studies on nature experiences often rely on generalized assumptions about the environment, overlooking the rich, contextual interactions that occur in specific settings (Spors et al., 2023). ZooWear addresses this gap by embedding nature experiences within the unique context of real-world zoos, blending immersive interactions with ecological learning, and addressing the lack of interactivity in traditional zoos. Our findings underscore the importance of context in shaping engagement, revealing that engagement is not merely about generalized or abstract notions of nature but deeply rooted in the specific characteristics, dynamics, and context of the zoos. First, zoos are unique public spaces that serve diverse audiences, each with distinct social relationships, needs, and expectations. Visitors range from children and teenagers to adults, all with different interests and engagement preferences (Hirskyj-Douglas et al., 2021). As such, personalized interaction mechanisms must be explored to cater to these varied demographics. Furthermore, zoos are inherently public spaces where social interaction is central. Beyond individual experiences, the design of interactive technologies should also consider group dynamics. Tools that facilitate group exploration or collaboration can enrich visitors' experiences, making zoo visits more enjoyable and educational for families, friends, and other social groups. Additionally, designing for zoos requires an approach that both shapes nature engagement and addresses the challenges and opportunities identified by stakeholders, such as attracting more visitors and enhancing animal welfare (Webber et al., 2020). Finally, the effectiveness of interactive feedback systems is also influenced by factors like noise levels, crowd density, and the unpredictability of animal behaviors. Cultural factors may also play a significant role in how visitors engage with the zoo experience (Tishler et al., 2020).

6.2.2. Virtual zoos as platforms for fantasy interaction

Unlike existing efforts that aim to replicate or restore real-world zoo environments in virtual settings (Sukmawati et al., 2023), our findings reveal the potential of incorporating imaginative and fictional narratives to create virtual zoo experiences diverging from reality. This approach enhances user

engagement and motivation by leveraging the unique affordances of virtual zoos—namely, their ability to construct immersive, fictional environments. By designing scenarios that go beyond reality, fantasy interactions, and even uncomfortable experiences—such as being pursued by wild animals or witnessing species extinction due to climate change—we transcend traditional representations of nature, which often emphasize serenity or tranquility (Spors et al., 2023). These interactions evoke a broader range of emotions, including awe, tension, and even fear, emotions that are seldom explored in conventional nature experiences. This emotional depth adds complexity to users' perceptions of nature, fostering more profound and reflective engagement. Such experiences make virtual zoos not only more immersive and memorable but also more meaningful, encouraging deeper reflection on real-world environmental challenges. However, it is essential to bridge fantasy with reality to ensure these experiences resonate with and inform users about actual ecological and societal issues. For instance, Cheng et al.'s *Moon Story* combines astronomy and environmental science with Chinese mythology, demonstrating how fantasy and educational content can seamlessly intertwine to create impactful and thought-provoking experiences (Cheng et al., 2024).

6.2.3. Wearable devices as key enablers

Prior research in human-nature interaction has leveraged the always-on, context-aware capabilities of wearable devices to facilitate closer interactions between humans and other species or to increase awareness of non-human life. For instance, *FloraWear* allows users to wear plants on their bodies, seamlessly merging human and non-human identities (Nam et al., n.d.). Devices such as *GoChirp*, a bird-wing-shaped bracelet, detect bird calls in the environment and alert users through wing flapping (Li et al., 2022). In this study, we explored the potential of wearable devices to act as identity markers, enabling users to adopt new perspectives (Phillips & Kau, 2019). We used animal-ear-shaped headsets to immerse visitors in specific animal perspectives. These devices allowed participants to physically embody animal behaviors, offering a multisensory experience that mirrored the ecological roles of the animals. Looking ahead, several directions can enhance the design of wearable devices for perspective-taking. First, wearables designed for this specific purpose should focus more on seamless integration between the user and the role they are playing. Currently, most devices respond passively to the environment, but future designs could emphasize the device as an extension of the user's body, with intuitive, embodied controls. For example, when the user is highly focused, the ears of the device could subtly move forward, mimicking animal-like attentiveness. Additionally, wearable devices should accommodate the diversity of users through modular and customizable designs (Kazemitabaar et al., 2017). Allowing users to personalize their devices—choosing shapes, materials, and functionalities that align with their desired animal role—can enhance both accessibility and engagement. Such adaptability would make these devices more inclusive and better suited to diverse audiences, thereby enriching the overall experience.

6.2.4. Sensory engagement as a facilitator

Previous research has extensively explored how sensory augmentation can enhance human interaction with natural environments, with a primary focus on visual and auditory modalities. For example, Immersive Flora visualizes natural elements perceived by plants through a virtual particle system (Hu et al., 2024), while Plantimus enables children to "hear" plants via an external sensory enhancement device (Asaf et al., 2021). In our study, ZooWear, we investigated the integration of haptic feedback as a medium to convey both informational and emotional cues during zoo visits. Several directions warrant further exploration. First, while we demonstrated the effectiveness of haptic cues, our user feedback aligns with findings from previous studies (Dalsgaard, 2022), indicating that the interpretation of haptic signals is often context-dependent and subject to individual judgment. Future designs should prioritize clarity and intuitiveness in the mapping of haptic feedback or explore enabling users to create their own feedback patterns. Second, expanding the range and combination of sensory interactions could enrich user experiences. For instance, in JeL, users synchronize their breathing with the rhythm of projected imagery, receiving corresponding visual feedback (Stepanova et al., 2020). Other studies have explored innovative haptic interactions, such as the potential of "playful biting" as a form of

haptic engagement with animal-inspired robots. These avenues highlight the need for deeper exploration into multisensory integration and the novel opportunities it offers for fostering meaningful connections with nature.

6.2.5. Narratives as drivers of long-term engagement

Building on sensory interactivity, our user feedback, aligned with previous research, highlights the essential role of cognitive and social interaction in promoting informal ecological learning and fostering long-term engagement (Sun et al., 2025). Future designs could integrate ecosystem phenomena, such as evolution, predation, and evasion, into narrative-driven system rules. These dynamics could be reflected in wearables and sensory feedback—for instance, a user's animal ears might bend to indicate an attack by a predator or gradually change over time to suggest maturation as the user becomes more immersed. Additionally, competitive or collaborative tasks could be introduced to enhance social interaction. For example, a user facing a predator alone might sustain injuries, but when multiple users embodying the same animal gather, they can collaboratively fend off the threat. Finally, integrating non-player characters (NPCs) (Steenstra et al., 2024) and utilizing generative artificial intelligence (Li et al., 2024) to craft open-ended, personalized narratives offers substantial potential. This AI-driven storytelling could dynamically adapt to user preferences, providing diverse and immersive experiences that deepen individual connections with the virtual ecosystem.

6.2.6. Adjustability for different zoo visit environments

Wearable devices are not only instruments for personal experience but also outward-facing media that naturally convey social signals (Kazemitabaar et al., 2017). For example, MakeWear shows that using wearables in learning opens opportunities for diverse feedback across social spheres (Kazemitabaar et al., 2017). Vasudevan et al. note that social feedback from in-class peer demonstrations and discussions fosters reciprocal learning (Vasudevan et al., 2015). In our experiments, we likewise observed that when two visitors toured together, the outward visibility of ZooWear often triggered social interaction and, in turn, additional collaborative learning. By contrast, during solo visits the device was invisible to the users themselves, making it difficult for them to visually observe changes in their ear movements, which may attenuate feedback-driven learning. Therefore, future designs should be adapted according to different scenarios. In multi-user contexts, in addition to enabling embodied, animal-perspective perception, systems can use wearables to render participants' behaviors and work states mutually visible (Marshall, 2007). Consistent with a constructionist view of learning as outcomes that accrue through ongoing interaction and environmental feedback (Kafai & Resnick, 2012), this visibility enables sensing to be noticed, responded to, and co-constructed in social exchange, thereby fostering collaborative learning and deepening empathy. In solo settings, where the social affordances of wearables may be constrained, virtual social compensation can be introduced. For instance, incorporating avatars or digital personae can reinforce embodied self-perception, allowing users to more intuitively monitor and perceive real-time changes, compensate for limited visual cues, and convey empathy, contextual understanding, and responsiveness (Freund, 2025). Additionally, network connectivity can support data sharing so that even solitary visitors can interact with others.

7. Limitations and future work

While our study demonstrates the potential of ZooWear in enhancing zoo visits through haptic feedback and animal perspective-taking, several limitations warrant further exploration in future research. First, although ZooWear showed short-term benefits in enhancing emotional engagement and knowledge retention, the long-term effects remain unclear. Future studies should investigate whether these impacts persist across repeated zoo visits and how they influence broader conservation awareness. Second, the participant group was primarily composed of young adults, which may not reflect the experiences of broader demographic groups, such as children, older adults, or international visitors. Expanding the sample size and diversity is essential to understanding how ZooWear might cater to different user needs.

8. Conclusion

In conclusion, we present ZooWear, a head-mounted wearable designed to enhance zoo visits by allowing users to experience the environment from an animal's perspective. By providing haptic feedback with different patterns when encountering various species, ZooWear offers an immersive and engaging way to explore the dynamics of the food chain. Both the quantitative and qualitative findings highlight the effectiveness of ZooWear in fostering meaningful human-animal-computer interaction and enriching the zoo experience. This research contributes to the growing body of work on integrating interactive technologies into zoo environments to facilitate visitor engagement and learning.

Author contributions

CRediT: **Pingting Chen**: Conceptualization, Investigation, Writing – original draft; **Bin Yu**: Supervision, Writing – review & editing; **Xiaoqing Sun**: Writing – original draft, Writing – review & editing; **Jiangnan Xia**: Conceptualization, Methodology; **Xinyu Liu**: Conceptualization, Software; **Xipei Ren**: Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing.

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