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Master's Thesis
Academic Year 2025

Designing a Breathing Simulation Device with Tactile Animal Features for Interactive Zoo Experiences

Keio University
Graduate School of Media Design

Luyao Huang

A Master's Thesis
submitted to Keio University Graduate School of Media Design
in partial fulfillment of the requirements for the degree of
Master of Media Design

Luyao Huang

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Abstract of Master's Thesis of Academic Year 2025

Designing a Breathing Simulation Device with Tactile Animal Features for Interactive Zoo Experiences

Category: Design

Summary

Modern zoo environments face the challenge of reducing physical contact with animals while maintaining meaningful visitor interaction. This study presents a non-contact tactile system that simulates animal breathing using soft, inflatable silicone integrated with authentic animal fur. Designed for children and families, the device translates physiological rhythms into rhythmic inflation-deflation cycles, enabling users to perceive life-like pulses through touch without disturbing live animals.

Three prototypes—llama, squirrel, and turtle—were developed with distinct breathing rates and surface textures. Using Arduino-based control, real fur integration, and 3D texture modeling, the system was refined through iterative design. It was publicly tested in two zoo workshops with over 100 participating families.

These findings suggest that tactile rhythm, surface realism, and narrative framing jointly contribute to affective engagement, offering practical insights for future zoo exhibit design. This work contributes to the growing body of research on embodied empathy and non-verbal, sensory-based learning experiences in public education spaces.

Keywords:

haptic interaction, non-contact zoo exhibit, breathing simulation, design thinking, educational prototyping

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Chapter 1
Introduction

1.1. Background: The Loss of Tactile Empathy in Zoos

In recent years, zoos and aquariums worldwide have increasingly adopted animal-centered exhibition and educational principles, placing animal welfare above visitor entertainment. The World Association of Zoos and Aquariums Code of Ethics and Animal Welfare emphasizes that institutions must ensure individual animals are free from hunger, discomfort, pain, fear, and are able to express normal behavior. As a result, many once-popular hands-on programs—such as "petting alpacas," "feeding goats," and "photo sessions with animals"—have been discontinued due to concerns about stress behaviors and long-term psychological harm to animals. For example, during a site interview in 2024, staff at Yumemigasaki Zoo explained that the alpaca petting program had been terminated after observing frequent signs of stress in the animals, including spitting, avoidance, and behavioral withdrawal. These decisions, while ethically sound, have also reshaped the visitor experience—especially for children—who now engage with animals only from a distance.

For young visitors in particular, the removal of tactile interaction can reduce animals to static displays rather than sentient, breathing beings. Touch is not only a sensory mechanism for acquiring information but also a powerful medium for forming emotional connections and empathy. As McGlone et al. have shown, slow and affectively charged tactile stimulation activates neural networks associated with social bonding and affiliative behavior [1]. This form of "affective touch" is one of the most primitive and fundamental channels through which humans develop haptic empathy. Paterson further argues that the sense of touch is not merely physical but deeply tied to emotional, cultural, and temporal dimensions of perception [2].

While zoos and museums have increasingly turned to non-contact technologies —such as projection mapping, ambient soundscapes, and augmented reality—to enrich visual and auditory engagement, the absence of authentic tactile feedback remains a critical barrier to emotionally resonant experiences [3]. Recent reviews of zoo education and exhibition strategies have emphasized the need to develop non-invasive sensory alternatives that support both visitor engagement and animal welfare, highlighting a shift toward "proximity without intrusion" as a future direction [4]. Studies in digital zoo exhibits have reported that the loss of touch significantly weakens children's sense of intimacy and empathy toward animals [5].

Moreover, earlier research indicates that emotional responses in zoo environments are more vivid when bodily engagement is present, even in simulated forms [6].

This research responds to that gap. It explores how tactile interaction—specifically the perception of rhythmic breathing through non-contact simulation—might offer an alternative channel for restoring empathy between visitors and animals. The goal is not to recreate physical touch, but rather to reintroduce a sense of bodily presence through subtle, rhythmically synchronized haptic cues.

By simulating lifelike breathing patterns with realistic fur textures through soft pneumatic motion, this project seeks to re-establish emotional proximity without direct animal contact. Unlike traditional haptic installations, this study emphasizes the integration of biological rhythm and surface realism to create an affective experience that aligns with both ethical standards and embodied empathy.

As one of the first zoo-deployed systems to combine rhythm-based haptics and real animal textures, it offers a novel approach to non-contact emotional interaction in educational contexts.

1.2. Design Approach: Breathing as a Medium of Connection

The inspiration for this project stems from a subtle, universally relatable moment —gently placing a hand on a pet or sleeping baby and sensing the rhythmic rise and fall of their breath. This small gesture, often accompanied by a spontaneous sense of calm or tenderness, embodies a form of silent, embodied communication that requires no words. Breathing, in this context, becomes more than a biological function; it is a sensory and emotional bridge between beings [2].

Building on this idea, the present research positions rhythmic breathing as a core interaction mechanism for restoring tactile empathy in zoo contexts. Rather than attempting to reintroduce physical touch—potentially compromising animal welfare—the project seeks to offer an alternative: allowing visitors, especially children, to feel a "breathing presence" through non-contact means. By simulating the cyclical inhale-exhale rhythms of different animals using pneumatic materials and soft robotics, the installation evokes an intimate bodily experience while maintaining ethical boundaries.

In contrast to many previous affective haptics projects that focus on wearable technology or human-to-human interaction, this research explores a novel domain of non-human, animal-based breathing simulation deployed in public education environments. The integration of real animal fur textures and species-specific breathing rhythms introduces a multisensory strategy that has not been widely explored in zoo-based installations.

This approach aligns with the emerging field of affective haptics, where technology is used to replicate emotional communication through touch [1]. Previous studies in wearable technology and interactive design have demonstrated that synchronized bodily rhythms—such as heartbeat and breath—can induce emotional attunement and physiological synchronization [7]. One recent study also suggests that individuals vary in their receptivity to affective haptic cues, reinforcing the need to consider user diversity in age, sensitivity, and background [8].Breathing, in particular, is a non-threatening and culturally neutral rhythm that can be simulated safely and meaningfully across diverse age groups.

This makes it particularly suitable for children and stress-sensitive visitors, offering a calming and emotionally accessible point of contact that does not rely on prior knowledge or language. By foregrounding gentle rhythmic feedback instead of visual spectacle, this project shifts the emphasis from passive observation to embodied presence and affective learning.

Pneumatic silicone provides a powerful material foundation for this design. Its adjustable softness, low thermal conductivity, and compatibility with embedded actuation systems make it ideal for simulating organic movement. When shaped using detailed 3D-printed molds and coupled with precision-controlled airflow, the material can produce lifelike pulsations that mimic an animal's respiration. Moreover, its medical-grade variants are hypoallergenic, easy to clean, and safe for repeated public use—key considerations for public exhibits in zoos. Building on this, it has also been found that silicone-based surfaces—when designed with attention to public use scenarios—can maintain both emotional effectiveness and high sanitary standards [9]. Thus, breathing is reimagined not as a metaphor but as an embodied interface. This research introduces a design strategy that treats breath as a tactile language—one that can cross the species barrier and gently reawaken a sense of emotional proximity in an increasingly mediated world.

1.3. Research Goal

This research aims to develop a non-contact tactile system that enables zoo visitors —particularly children—to regain a sense of physical and emotional connection with animals, even in the absence of direct interaction. By simulating two key physiological features—breathing rhythm and skin/fur texture—through a pneumatic silicone prototype, the project seeks to reintroduce bodily presence as a medium for empathy.

The central idea is not to replicate the entire tactile experience of touching an animal, but rather to abstract and distill one of its most emotionally resonant components: the feeling of life conveyed through rhythmic movement. The gentle rise and fall of simulated breath offers a subtle yet powerful cue that something is “alive” and “present.” When enhanced with bio-inspired surface textures and —where possible—genuine fur samples, the device aims to deliver a multisensory experience that triggers recognition, curiosity, and affective engagement.

From a design perspective, this research also explores how materials, rhythm, and form can be orchestrated to convey lifelikeness and emotional tone without relying on screens or traditional animations. The emphasis is on tactile minimalism: delivering high emotional impact through low-complexity, soft interfaces that are safe, durable, and easy to maintain in public settings.

Importantly, the system is not intended solely as a product prototype, but as a part of a broader service design approach tailored to public zoo contexts. It explores how interaction systems can be holistically designed to balance emotional learning with logistical constraints such as durability, safety, and hygiene.

Ultimately, this project contributes to the ongoing rethinking of zoo-based interaction models. It proposes an alternative paradigm—empathy through simulation rather than interaction—that preserves animal welfare while fostering embodied learning and emotional resonance. The system is designed not just as a technical solution, but as a communicative medium that reconnects humans and animals through the language of breath.

As one of the few projects to be prototyped and tested within an actual zoo setting, it provides early-stage empirical insight into how haptic simulation may be integrated into public education infrastructure. This research aims to lay the groundwork for future studies in affective tactile experiences beyond traditional human-computer interaction scenarios.

1.4. Research Questions

This study addresses the following questions to evaluate the effectiveness of a breathing simulation device with tactile animal features in zoo settings:

1. Can a breathing simulation device with tactile animal features foster emotional empathy and engagement, particularly among child visitors?
2. How do variations in breathing rhythm and tactile texture affect visitors' perception and recognition of different animal models?
3. Does adding genuine animal fur enhance perceived realism and emotional engagement compared to silicone texture alone?

1.5. Thesis Structure

The first chapter introduces the motivation and background of this research. It outlines the growing limitations of physical interaction in modern zoos due to ethical and animal welfare concerns, particularly the elimination of touch-based programs. It also explains the concept of tactile empathy and justifies the use of breathing simulation as an alternative emotional interface. The research objectives and questions are defined at the end of the chapter.

The second chapter reviews prior research in haptic interaction, soft pneumatic materials, breathing rhythm as a communication modality, and non-contact interaction in zoo and museum contexts. It identifies theoretical and technical gaps in existing work and positions this study within the interdisciplinary fields of interaction design, affective computing, and educational exhibition.

The third chapter describes the design process of the prototype, including three stages of development. It presents the evolution from an early silicone model to upgraded versions incorporating animal fur and texture improvements, following stakeholder feedback from zoo staff. The chapter also reflects on design rationale, materials used, and the iterative integration of tactile and rhythmic elements.

The fourth chapter details the evaluation methodology and user testing. It covers a controlled indoor experiment and two public workshops conducted at the zoo. This chapter analyzes both quantitative and qualitative data, compares user feedback across prototype versions, and highlights participant reactions to different animal breathing patterns and textures.

The final chapter concludes the study by summarizing key findings and academic contributions. It discusses design implications, addresses limitations, and suggests future directions for expanding the breathing interface to other contexts, such as educational tools or therapeutic environments.

Chapter 2
Literature Review

2.1. Haptic Empathy through Rhythm and Texture

In interactive design, touch is increasingly understood not only as a tool for perception but as a channel for emotional communication. Haptic empathy refers to the phenomenon in which tactile stimuli evoke emotional resonance between humans or between humans and other beings, even in the absence of direct contact. This form of empathy is particularly relevant in zoo contexts, where traditional touch-based experiences are being replaced by mediated or non-contact interactions.

Recent neurophysiological studies suggest that not all touch is processed equally. Human tactile perception includes both discriminative touch, responsible for detecting spatial and surface features, and affective touch, which conveys emotional and social meaning. Affective touch is typically slow and rhythmic, activating a specific type of nerve fiber—C-tactile (CT) afferents—that are strongly linked to feelings of social comfort and bonding [1]. This type of touch has been associated with increased activation in brain regions related to emotional processing, suggesting that rhythmically delivered tactile input can contribute to perceived interpersonal closeness.

Haptic empathy also correlates closely with physiological synchrony—shared patterns of bodily rhythms such as breathing or heart rate between individuals. Studies in behavioral neuroscience have demonstrated that such synchrony enhances emotional contagion and mutual understanding, particularly in close social relationships [7]. Additionally, individual differences in affective haptic sensitivity have been identified as important design considerations in empathy-based interfaces [8].

The phenomenological dimensions of haptic experience further underscore its potential for affective communication. Touch does not operate in isolation but interacts with cultural memory, past experiences, and social expectations. Rhythmic tactile feedback, especially when subtle and continuous, may evoke memories of care, intimacy, or animal companionship, thereby strengthening users' emotional investment in the interaction [2]. In this context, breathing—characterized by continuous, low-frequency, biologically grounded rhythms—presents a particularly promising modality for haptic simulation.

Material characteristics also influence the emotional expressiveness of touch. Natural surfaces such as fur are more likely to evoke warmth, comfort, or surprise compared to synthetic materials, emphasizing the importance of tactile realism in affective design (Figure 2.1) [10].

Source: Iosifyan and Korolkova, Consciousness and Cognition, 2019 [10]

Figure 2.1 Twenty-one items with different textures

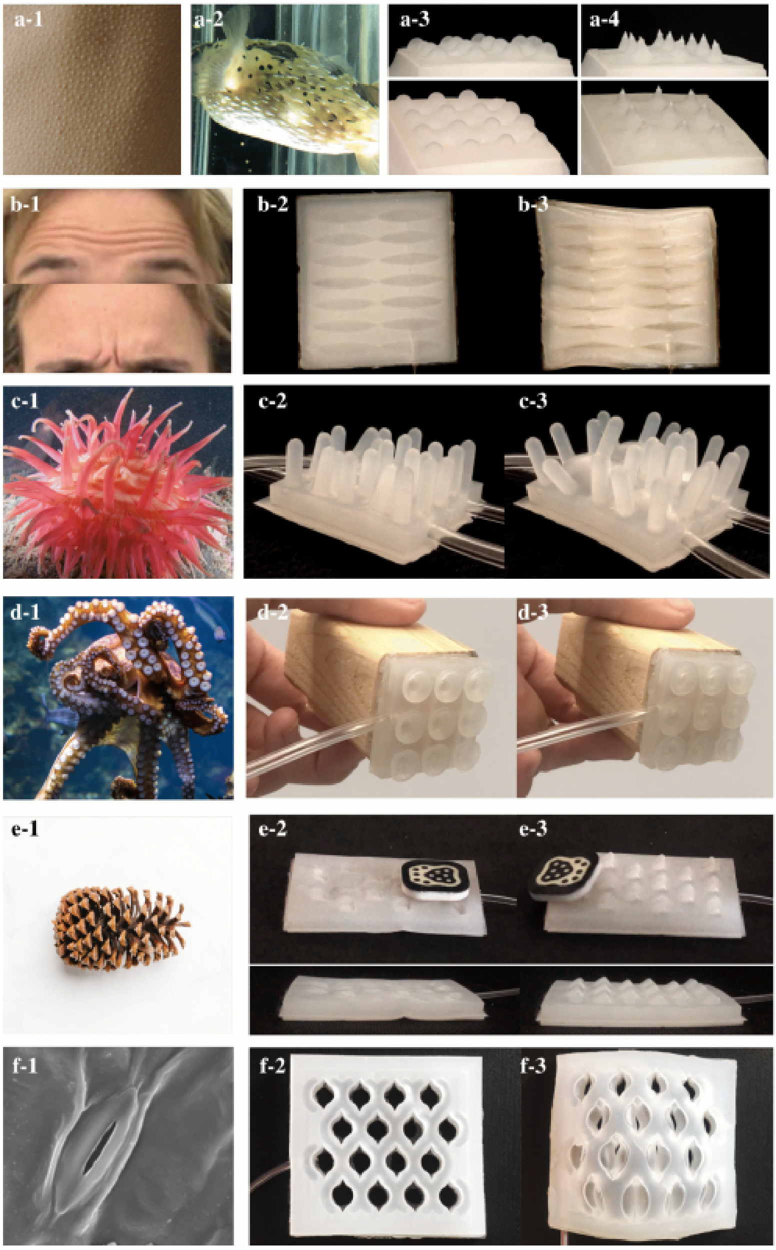
Research in visuo-haptic simulation has demonstrated that fur's directional and voluminous qualities enable a more immersive and lifelike sensory experience [11]. Gentle touch has also been shown to exert calming and affiliative effects across human-animal-robot interaction contexts, reinforcing its universal function in emotional bonding [12].

Additional findings suggest that rhythmic tactile input not only elicits empathy but also enhances memory retention and narrative absorption, particularly when integrated into sensory learning experiences [13]. These insights support the overarching goal of this research: to restore a sense of bodily presence and empathetic understanding in zoo visitors without compromising animal welfare.

2.2. Soft Pneumatic Interfaces and Tactile Technologies

The development of soft pneumatic interfaces has introduced new possibilities for delivering lifelike haptic feedback in interactive systems. Unlike rigid actuators, soft pneumatic devices are composed of flexible, deformable materials that can bend, expand, and contract in response to air pressure. These qualities make them particularly well-suited for applications requiring safety, subtlety, and organic motion, such as human-robot interaction and bio-inspired design.

Recent work in soft robotics has demonstrated that fiber-reinforced elastomers and other deformable structures can be engineered to achieve programmable movement patterns. By varying internal fiber angles and chamber geometries, actuators can inflate asymmetrically, producing controlled bending or pulsing motion. This allows designers to simulate biological rhythms or expressive gestures with high fidelity [14]. Such technologies are especially relevant in contexts where tactile realism and emotional resonance are key—such as simulating the slow, rhythmic motion of breathing.Recent advances using differentiable simulation allow soft actuator performance to be predicted more precisely, which improves the quality and responsiveness of rhythmic motion in interactive applications [15]. These soft systems can also integrate with pneumatic controllers to achieve dynamic, responsive interactions. Distributed air chambers and timing algorithms enable actuators to breathe, ripple, or compress in rhythm with external inputs or preprogrammed physiological patterns [16]. Breathing simulation has emerged as a targeted application, where cyclic inflation and deflation recreate the visual and tactile cues of respiration. These systems are reported to outperform both visual-only and tactile-only setups in terms of emotional impact and immersive experience [17].Wearable implementations have used rhythmic soft actuation to communicate breathing cues and foster emotional closeness in interpersonal interaction (Figure 2.2) [18].



Source: Heather Culbertson al. from DIS 2022 [18]

Figure 2.2 Bio-inspired skin prototypes for expression

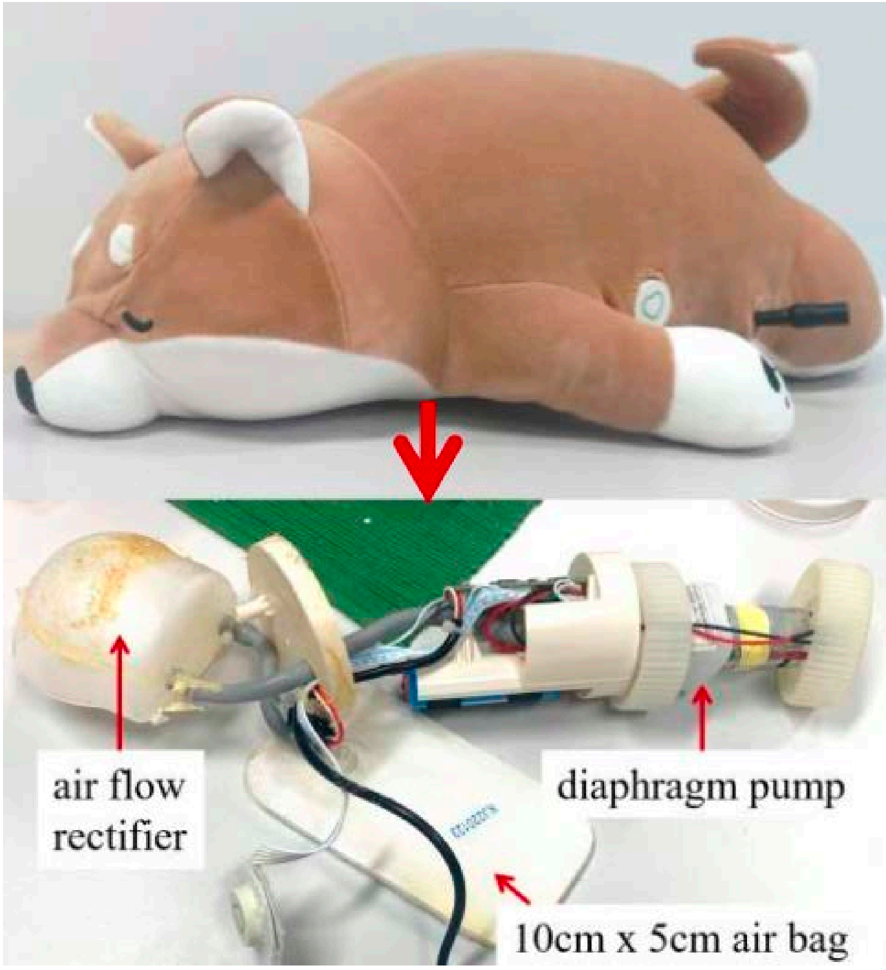
The selection of materials—whether elastomers, plastics, or textiles—plays a significant role in shaping user perception. Soft interfaces can be tuned in terms of stiffness, surface texture, and deformation characteristics to simulate the feel of biological surfaces such as skin, muscle, or fur. This versatility supports applications in educational and therapeutic contexts, where both safety and sensory realism are essential.

In summary, soft pneumatic actuators and flexible interface materials provide a robust technical foundation for the development of haptic breathing simulators. Their flexibility, programmability, and rhythmic motion make them ideal for simulating biologically grounded interactions in zoo environments, where direct physical contact is no longer viable but embodied experience remains essential.

2.3. Recreating Animal Physiological Signals

The tactile simulation of physiological signals—such as breathing and heartbeat—has become an effective strategy for eliciting empathy and emotional engagement in mediated environments. These signals are inherently rhythmic and affective, closely tied to perceptions of aliveness and connection. Delivering such rhythms through touch provides an alternative sensory pathway for engagement, particularly in non-verbal and animal-centered contexts.

Simulated physiological rhythms, such as slow inflation-deflation or pulsation patterns, have been shown to enhance perceived lifelikeness and emotional resonance. When rendered with appropriate frequency and amplitude, these cues allow users to interpret the presence of life through bodily sensation. Research suggests that even subtle low-frequency tactile feedback can simulate heartbeats or breathing cycles in a way that reduces anxiety and increases affective connection [19] Breathing patterns are particularly impactful due to their cyclic, grounding quality.



Source: Minori Tsuji al. from IEEE ARIS 2024 [17]

Figure 2.3 Pneumatic mechanism inside plush animal simulating breathing

In animal-themed installations, combining rhythmic motion with symbolic representations has been shown to intensify immersion and empathy [17]. One representative system embeds a pneumatic mechanism inside a plush animal, allowing users to feel simulated breathing through the surface (Figure 2.3). The actuation system consists of a diaphragm pump, air flow rectifier, and an airbag housed within soft padding materials.

In parallel, other studies have explored the simulation of animal heartbeats as a method for evoking awareness of biological diversity through tactile comparison.

Source: Heather Culbertson al. from DIS 2022 [20]

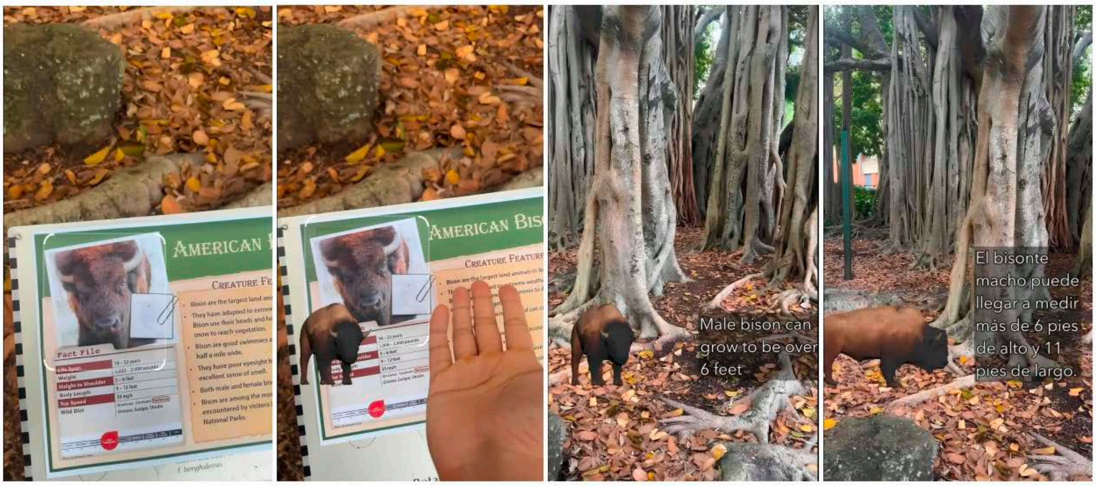
Figure 2.4 SOL: An installation comparing heartbeats across species

SENSE OF LIFE (Figure 2.4), for example, is an interactive installation that enables users to physically compare the heart rates of multiple species—such as rabbits (240 bpm), humans (60 bpm), and elephants (30 bpm)—by touching embedded low-frequency actuators designed to reproduce each species' cardiac rhythm. While not explicitly developed for zoo environments, this system demonstrates how cross-species rhythm simulation can foster somatic empathy through rhythmic comparison and reflection [20].

This form of bio-rhythmic haptics is especially valuable in educational or therapeutic settings, where the tactile sensation of breathing or heartbeat can evoke a sense of calm and emotional presence. Importantly, the goal is not medical precision but the perceptual suggestion of life—using rhythm, softness, and repetition to encourage connection. In zoo environments, such approaches may help children better perceive animals as sentient beings despite the lack of direct contact.

2.4. Non-Contact Interaction in Contexts

In response to growing concerns about animal welfare, traditional contact-based programs in zoos—such as petting or feeding—have increasingly been restricted or eliminated. This has created a gap in emotional engagement, particularly for children who rely on physical experience to build empathy with animals. A global review of visitor-animal interactions confirms that direct-contact attractions often trigger stress responses in animals and may compromise long-term welfare, encouraging institutions to explore more ethical, non-contact alternatives [21]. In this context, non-contact interaction systems have emerged as a solution to offer immersive, educational experiences without direct animal involvement.



Source: Brandon Victor Syiem al. from DIS 2024 [22]

Figure 2.5 AR Prototype for Multilingual and Interactive Animal Information Display

Interactive technologies in zoos have evolved to create new modes of human-animal engagement. Digital installations incorporating sensors, screens, and spatial audio have demonstrated potential to evoke emotional responses similar to real-life animal encounters [5]. Previous case studies in zoo environments have shown that even screen-based or auditory interactions can elevate the perceived agency of animals and improve visitor satisfaction in the absence of touch [23]. In particular, augmented reality (AR) has emerged as a promising tool to enhance zoo-based experiences through digital overlays and contextual visualizations (Figure 2.5). Recent research demonstrates that AR-enhanced exhibits can significantly improve children's curiosity, engagement, and long-term memory retention by aligning sensory novelty with narrative immersion [22]. These systems aim to compensate for the loss of physical contact by intensifying other sensory channels, such as synchronized visuals and responsive ambient sounds. Institutional frameworks have also started to support this transition toward non-contact modalities.

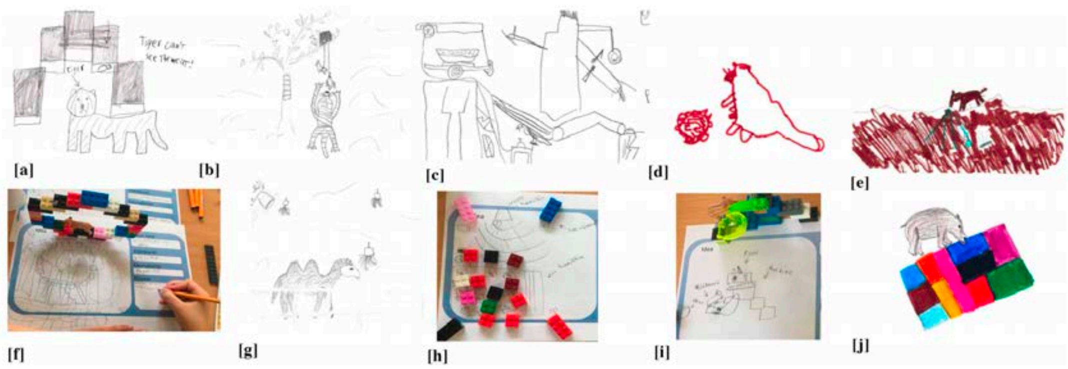
A notable example of tactile-based non-contact interaction is the "Sawaru Ogasawara" project, jointly developed by Taica Corporation and Chizaizukan Inc. in collaboration with Sumida Aquarium. This initiative introduced a series of educational goods that replicate the unique surface textures of endangered animals from the Ogasawara Islands using GEL, a multifunctional silicone gel renowned for its ability to mimic diverse tactile sensations. Officially launched in 2023 as part of the "Ogasawara Lab" educational tourism platform, the products aimed to foster emotional connection and biodiversity awareness by enabling touch-based learning without involving live animals. Aquarium staff oversaw the development to ensure the realism and educational value of the simulated textures [24].

Source: Taica Corporation and Chizaizukan Inc. [24]

Figure 2.6 Tactile animal learning items using GEL to replicate the surface textures of rare Ogasawara species

International guidelines now emphasize visitor education and welfare-centric design without relying on physical animal contact [4]. Studies show that such installations can significantly enhance visitor attention and dwell time, especially among young audiences [3].

Recent approaches have moved beyond passive content delivery by involving children in co-creating interaction experiences. For example, guidebook-style applications have enabled young visitors to explore zoo narratives through playful tasks and avatar-based storytelling, resulting in improved empathy and engagement [25]. Further studies have shown that children's learning in zoos is shaped not only by what is presented but also by how the space allows them to participate and construct meaning through gesture, drawing, and collaborative movement (Figure 2.7) [26]. Playful co-design approaches have also been explored to improve children's learning outcomes in zoo contexts. By involving children in the creation of interactive content—such as designing digital animal companions or modifying exhibit responses—educators report higher levels of engagement, agency, and recall [3]. This aligns with broader findings in exhibit design that emphasize emotional resonance as a key factor influencing visitor satisfaction [27].



Source: Lian Loke al. from DIS 2023 [26]

Figure 2.7 A selection from the range of children's drawings

Moreover, research into the "visitor effect" suggests that elevated human presence and contact can lead to stress responses in zoo animals, reinforcing the value of non-invasive interaction systems [21]. Insights from museum-based research also support this direction. It has been noted that family groups in museum settings often co-construct meaning through gesture and mediated tactile actions, creating shared emotional and educational experiences [28].This suggests that even abstracted or simulated touch can meaningfully support social bonding, particularly between children and caregivers in educational contexts.These insights support a paradigm shift in exhibit strategy: from animal-centric touch to visitor-centric empathy, supported by mediated sensory experience.

In sum, non-contact interaction technologies are not only practical adaptations to ethical constraints, but also opportunities to reframe zoo-based education through multisensory, affective experiences that resonate with diverse visitors.

2.5. Research Gap and Our Contribution

While affective touch has been widely studied in both neuroscience and interaction design, and physiological synchrony has been linked to emotional resonance in social and therapeutic contexts [1] [29], few projects have systematically translated these insights into tactile systems designed for zoo or museum settings. Most existing zoo-based interaction designs continue to rely heavily on visual or auditory feedback, with limited integration of tactile elements beyond simple surface textures or vibration effects. Despite existing evidence that physical engagement in zoo environments enhances empathy and conservation learning—especially among children [30]—most interaction designs remain visually dominant, rarely integrating touch beyond simple textures or vibrations. This visual-dominant trend persists despite increasing awareness of touch's role in emotional learning, particularly for children.

Although some pioneering works have recreated animal physiological rhythms —such as breathing patterns or heartbeats—to elicit empathy and immersion [17], these systems are often presented as artistic prototypes or limited-scope installations, typically evaluated for novelty or affective impact rather than pedagogical effectiveness or long-term educational use. Projects using soft silicone-based materials to simulate the surface textures of rare animals have also been explored in aquarium settings, such as tactile installations developed for biodiversity awareness at Sumida Aquarium [24], but these focus mainly on surface realism rather than dynamic physiological simulation.

Existing research has highlighted the importance of tactile engagement in early emotional and cognitive development. For instance, soft and rhythmic stimuli have been found to contribute to children's perception of lifelikeness and empathy [13].

Related studies show that rhythm-based sensory feedback, when designed with appropriate pacing and material quality, can foster a more accessible and inclusive educational experience across diverse user groups [29].

In terms of materials, previous investigations into pediatric haptic preferences suggest that softness and elasticity in tactile surfaces are strongly associated with positive emotional responses. However, few tactile systems have taken into account how material parameters—such as Shore A hardness or surface texture—can be optimized to support empathetic interaction, particularly in the context of zoo exhibitions.

Moreover, while soft robotics and pneumatic materials have advanced significantly, few studies have deployed these technologies in sustained, user-tested educational environments. Breathing and heartbeat simulations are typically used as temporary sensory enhancements rather than deeply integrated pedagogical tools. The absence of design frameworks that bridge emotional experience, tactile fidelity, and learning outcomes remains a significant challenge.

To address these gaps, this research introduces a soft pneumatic interaction system that mimics animal breathing patterns through embedded air pressure control and medical-grade silicone membranes. The system aims to evoke emotional empathy and embodied engagement, particularly for children in non-contact zoo environments. In contrast to previous short-term installations, the presented prototypes are tested in both controlled lab settings and real-world public zoo workshops, with iterative feedback gathered from children, parents, and zoo staff. In addition, each prototype is designed not only to simulate realistic breathing rhythms but also to integrate tactile textures and optional fur elements for multisensory effect.

By focusing on biologically grounded breathing rhythms and emotionally resonant material cues, this research proposes a new paradigm for tactile interaction in educational and public spaces. It synthesizes insights from affective haptics, soft robotics, and early childhood education into a cohesive system that supports emotional development, ethical engagement, and inclusive learning.

Chapter 3
Design Progress

3.1. Design Concept and Interaction Philosophy

As hands-on animal interactions are increasingly restricted in zoos for ethical and welfare reasons, a significant gap has emerged in how visitors—especially children—emotionally engage with animals. To address this, our design concept proposes a tactile interaction system that transforms breathing into a medium of empathy. Breathing, as one of the most fundamental and universally shared physiological rhythms, carries an emotional and biological significance that can be intuitively recognized across species.

Our design reinterprets breathing as a subtle, bodily signal of life, one that can be transmitted through soft, rhythmic touch. Instead of relying solely on visual or auditory media—which can often feel distant and abstract—this system invites users to feel the rise and fall of an animal-like torso, simulating real-time inhale‑exhale cycles. By embedding species-specific breathing frequencies into the system, the simulator creates a rhythmic embodiment that reflects the unique tempo of different animals, from the fast-paced breath of a squirrel to the slow, steady rhythm of a turtle.

To enhance realism, the simulator incorporates biomimetic tactility through medical-grade silicone molds with detailed skin and fur textures. These tactile surfaces are achieved by casting with 3D-printed molds and integrating real or synthetic animal hair, enabling users to distinguish animal types not only through rhythm but also through touch. The resulting experience blends soft robotics with emotionally resonant materiality, allowing visitors—particularly children—to form intuitive and affective connections with representations of living creatures.

Moreover, this design is embedded within a broader service flow aimed at educational engagement. The system is intended to support zoo educators in storytelling, facilitate parent-child exploration, and provide multisensory entry points to animal knowledge. It is designed to be installed in touch-free areas such as exhibit corners, children's activity zones, or pop-up learning stations, functioning as both a stand-alone experience and part of a guided learning tour.

To ensure ethical compliance and continuous usability, the entire interaction is designed to occur in a non-contact format, ensuring no disturbance to real animals. The system operates independently of animal presence, making it scalable, low-maintenance, and suitable for continuous public interaction. It functions not merely as a technological novelty but as a new educational medium: one that reintroduces the sense of "living presence" to zoo exhibits and encourages a deeper understanding of animal life beyond observation.

In summary, this design concept proposes a shift from passive visual consumption to active bodily engagement through rhythmic tactile experiences. By translating animal breathing into a material form that can be touched, the project aims to restore emotional depth and embodied empathy in non-contact zoo environments.

3.2. Prototype I -Silicone-Based Elephant

3.2.1 Concept Overview

The first prototype was created as an initial attempt to simulate the rhythmic breathing of animals using pneumatic silicone structures. The elephant was selected as the target species due to its iconic status and its naturally slow, deep breathing rhythm, which made it ideal for initial rhythm modeling. This early stage focused on establishing the technical feasibility of using inflation and deflation cycles to convey a sense of life through motion and tactility. The goal of this phase was to test the feasibility of combining tactile texture reproduction and low-frequency inflation-deflation cycles to convey lifelike presence (Figures 3.1). Rather than aiming for direct zoo deployment, this prototype served as an exploratory model to validate core interaction principles, such as breath pacing, soft tissue simulation, and the tactile realism of skin-like surfaces.

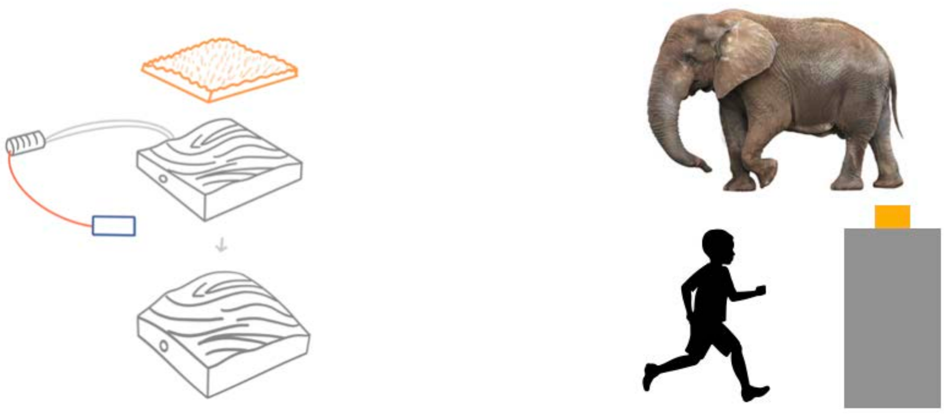


Figure 3.1 Early prototypes of the breathing simulation system for elephants

3.2.2 3D Printing and Silicone Molding Process

To recreate the wrinkled texture of elephant skin, high-resolution photographic references were processed using OpenCV and Gabor filtering to extract tactile features. These features were converted into 3D meshes and printed using PLA filament on a Bambu Lab printer (25 μm resolution). The resulting molds captured up to 0.6 mm of texture depth. This pipeline allowed the team to achieve micro-scale fidelity in the simulated skin texture, which is essential for evoking a realistic tactile impression.

The fabrication of the inflatable silicone chamber was carried out through a multi-step mold casting process (Figure 3.2). First, the inner surface of the 3D-printed mold was coated with a release agent. A layer of medical-grade silicone (HTV2000 or HTV4000) was poured into the mold to form the bottom half of the skin. Once the surface had partially cured (semi-solidified), a thin plastic square film—sized approximately 0.5 cm smaller than the silicone boundary—was gently placed on top. This layer acted as an internal barrier to form the air cavity. To prevent undesired adhesion, a fine layer of dry powder (e.g., talc or cornstarch) was also applied across the plastic membrane. Next, a short section of flexible tubing was inserted at the edge of the mold between the first layer and the mold wall, functioning as the future air inlet/outlet. Then, a second layer of silicone was poured to cover the top, sealing the plastic film and tubing between the two

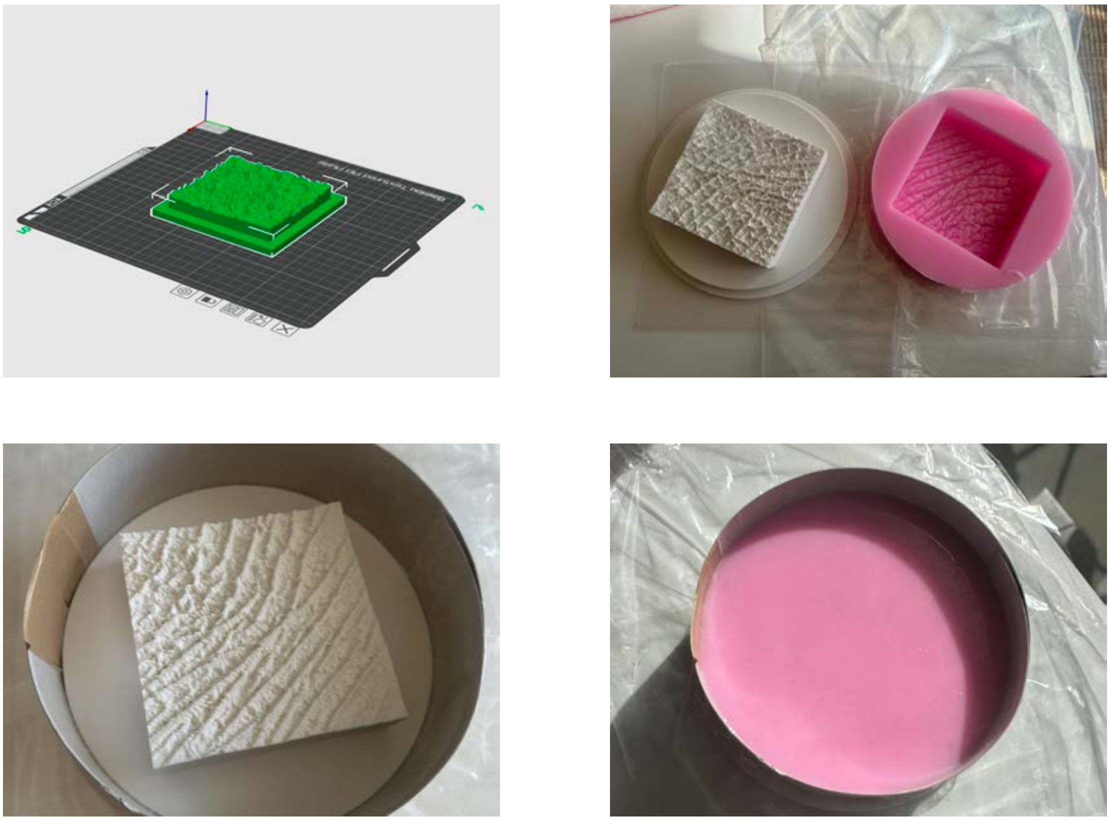


Figure 3.2 Fabrication process of the inflatable dual-layer silicone model

silicone layers. After full curing, the model was demolded, and the embedded plastic film formed a sealed inner air cavity. The pre-positioned tube created a secure channel through which air could be pumped into the structure.

The design ensured a clean division between layers while maintaining a flexible yet durable edge structure to withstand repeated inflation. The resulting inflatable silicone structure was then connected to a balloon pump or a programmable vacuum pump for initial inflation trials. This iterative casting method not only allowed the refinement of skin thickness and texture response, but also set a repeatable fabrication process for subsequent prototypes.

To evaluate the softness, elasticity, and structural integrity required for inflating skin-like structures, three silicone formulations were tested during the prototyping process. HTV2000, with a Shore A hardness of approximately 20, provided a soft yet moderately flexible texture and was used as the primary material in most inflatable structures. HTV4000, measuring around Shore A 40, offered a firmer and more shape-retentive surface, suitable for parts requiring greater form stability during repeated inflation cycles.

Additionally, a Platinum Cure Silicone—rated close to Shore A 0—was briefly tested for its extreme softness and tackiness. While this ultra-soft silicone delivered high adhesion and lifelike pliability, it proved structurally unstable under pressure and prone to tearing, making it unsuitable for pneumatic inflation in practical settings (Figure 3.3). Therefore, it was excluded from further implementation but remains an informative reference in the exploration of tactile softness extremes.

Figure 3.3 Comparison of silicone samples

These comparative tests revealed that tactile realism alone cannot override functional durability in long-term public settings. HTV2000 was ultimately chosen for balancing softness with resilience, particularly under high-frequency interaction scenarios such as children' s repeated grasping. The findings also informed future material selections for other animal prototypes, where surface softness and memory retention were matched to species-specific tactile expectations. This early-stage material analysis contributed significantly to the iterative design process, guiding the appropriate pairing of sensory realism and engineering feasibility.

3.2.3 Pneumatic Structure and Breathing Simulation

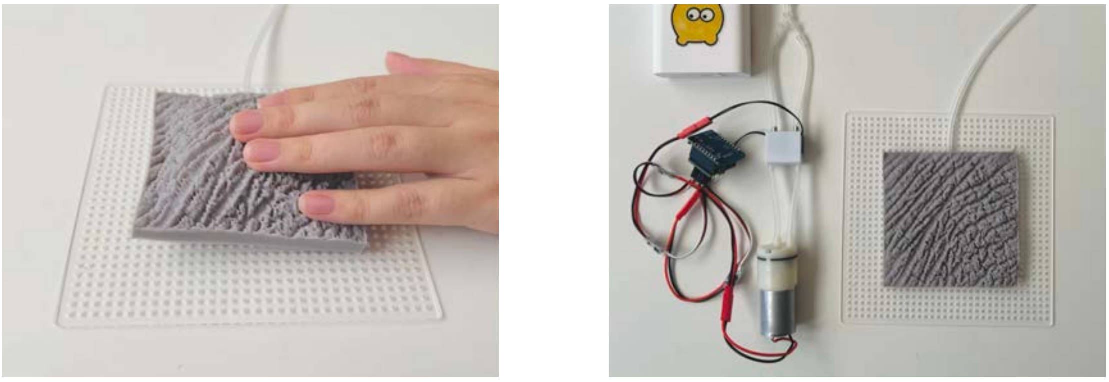


Figure 3.4 Pneumatic control system for simulating elephant breathing

To replicate the deep, slow respiratory motion of an elephant, the prototype integrated a programmable pneumatic system powered by a 370-series cylindrical vacuum pump. This compact component supports both inhalation and exhalation via dual-direction ports, reducing overall weight and simplifying assembly.

Airflow is directed through medical-grade silicone tubing and controlled by a three-way solenoid valve, which toggles between inflation and deflation. The valve, along with the pump, is governed by a PWM electronic switch (3 - 5 V) connected to an ESP8266 development board, enabling real-time programmable control (Figure 3.4).

The breathing rhythm was pre-programmed to simulate the resting frequency of an adult elephant—approximately 6 to 12 breaths per minute. To avoid mechanical repetition and enhance biomimetic expressivity, the control logic injected random fluctuations of 100 - 300 milliseconds in each breathing cycle. These subtle irregularities helped build a more lifelike presence, making the inflation rhythm feel organic and emotionally resonant.

Throughout testing, inflation response delays were consistently kept under 200 milliseconds, ensuring tactile synchrony between visitor contact and rhythmic motion. After 5,000 continuous cycles, all components—including the vacuum pump, solenoid valve, and silicone chamber—remained stable and responsive. This confirmed the system's durability, control precision, and capacity to simulate lifelike breathing through a soft, safe, and low-maintenance configuration —laying a solid technical foundation for future animal-specific iterations.

3.2.4 Onsite Presentation and Feedback

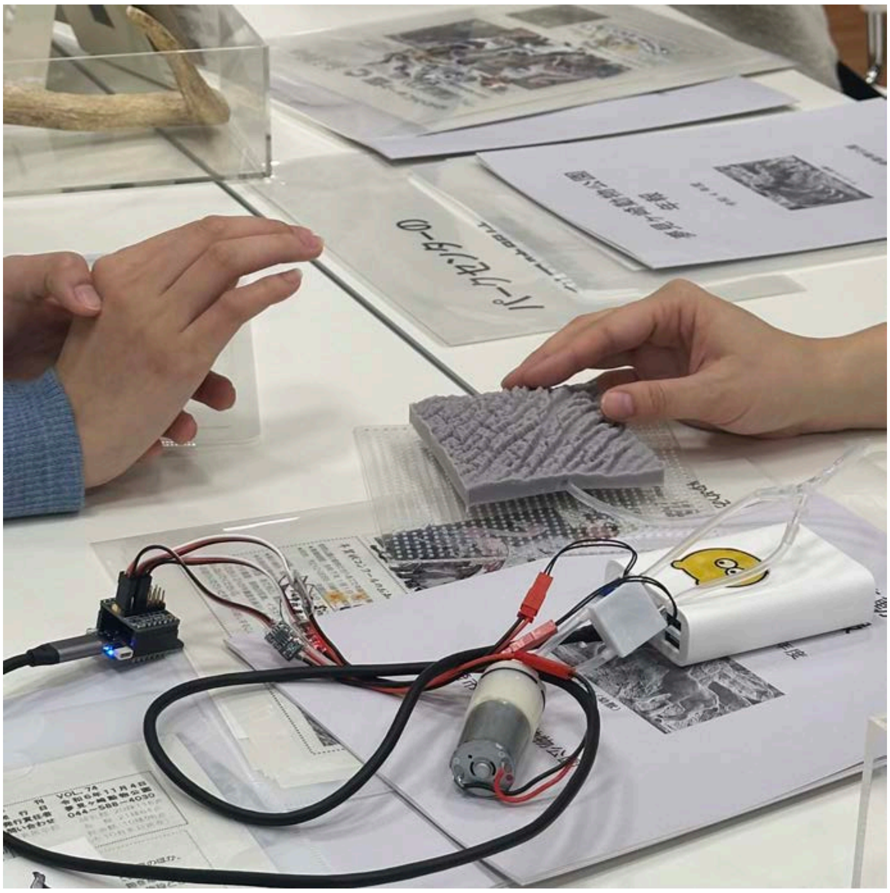


Figure 3.5 Prototype presentation during initial collaboration meeting

This prototype was presented during the first collaboration meeting (Figure 3.5) with staff at Yumemigasaki Zoo, serving as both a technological demonstrator and a service design probe. Although the zoo does not house elephants, the prototype's texture fidelity and rhythmic breathing simulation intrigued staff, highlighting its potential for emotionally engaging children even in the absence of live animals.

The meeting did not only validate tactile realism but also revealed critical insights about content alignment and species relevance. staff emphasized the importance of choosing species already familiar to local children, both for relevance and educational alignment. As elephants were not part of the zoo's collection, they recommended focusing on in-zoo animals such as llamas, which had previously been part of a discontinued petting program. The main reason for cancellation had been animal stress and hygiene concerns, but the concept of non-contact, tactile rhythm simulation was seen as a promising educational replacement.

Figure 3.6 Actual llama fur from past educational materials

Additionally, staff offered real llama fur samples from past educational materials (Figure 3.6), encouraging its incorporation to enhance tactile realism and emotional resonance. This gesture marked the start of a co-creative relationship with the zoo, in which feedback directly shaped subsequent design decisions such as species selection, fur attachment method, and contextual installation possibilities.

Importantly, this meeting represented more than feedback on form—it served as the pivot from lab-driven exploration to context-aware, service-integrated prototyping. Design choices such as material hardness, breathing control frequency, and modular form factor were revisited not only for technical optimization but also for their educational and operational fit within zoo environments. This encounter ultimately laid the groundwork for the animal-specific, field-adapted prototypes that followed.

3.3. Prototype II -Hair-Integrated Prototypes

3.3.1 Animal Prototype Selection Process

Following the initial prototype demonstration, the project direction was realigned to better fit the needs of Yumemigasaki Zoo's educational environment and visitor demographics, particularly children. While the elephant prototype successfully simulated rhythmic breathing and tactile realism, feedback from zoo staff emphasized the importance of selecting animals familiar to local children to increase emotional relevance and learning resonance.

Based on this feedback, the team introduced three new prototypes corresponding to animals within the zoo's actual collection: llama, squirrel, and turtle. Each was chosen to represent distinct combinations of respiratory rhythm and tactile texture, thus forming a diverse and comparative sensory palette for children's interaction.

The llama, with a moderate breathing rate of 15 to 25 breaths per minute, was chosen for its soft fleece and gentle appearance. Staff provided actual fur samples from previous educational materials, which enabled a realistic integration of authentic tactile surfaces.

The squirrel, breathing rapidly at 60 to 80 breaths per minute, was selected for its small body and short, fine fur—offering high-frequency inflation cycles and a compact tactile area suitable for finger-based exploration.

The turtle, although known for its rigid shell, was represented through the dry, textured skin on its limbs. With a slow breathing rhythm of 6 to 12 breaths per minute, this prototype introduced subtle inflation cues and coarse textures to contrast with the other models.

Importantly, these animals were not only physically accessible in the zoo's exhibits, but also cognitively recognizable by children, making them ideal for bridging tactile simulation with biological education. The selection also reflected a deliberate variation in texture (soft, fine, rough) and rhythm (fast, moderate, slow), enabling children to intuitively compare the "feel" of how different animals breathe—a sensory dimension rarely emphasized in traditional zoo displays.

3.3.2 Prototype Construction and Hair Integration

In the second prototype iteration, each animal prototype was tailored not only in terms of breathing rhythm but also in tactile design and physical dimensions, reflecting both physiological realism and material affordances. The prototypes were scaled according to the relative body sizes of the actual animals, providing intuitive reference points for visitors—especially children—to associate size with species. Specifically, the llama prototype measured approximately 15 $\times$ 15 cm, the turtle prototype 9 $\times$ 9 cm, and the squirrel prototype 3 $\times$ 3 cm (Figure 3.7).

Figure 3.7 Relative sizes of three prototypes to support species recognition

Among the three, only the turtle prototype featured a surface texture, created by printing a high-resolution mold (25 μm precision) using PLA filament and casting with HTV4000 silicone (Shore A $\approx$ 40) to reproduce the characteristic fine ridges of the turtle's dry, leathery skin. In contrast, the llama and squirrel prototypes used smooth inflatable silicone chambers without embedded textures. This decision was made to accommodate the application of a Platinum Cure Silicone interface layer, onto which authentic llama fleece and squirrel fur were affixed to simulate lifelike animal surfaces.

Figure 3.8 Species-specific prototypes with real fur

The hair integration process (Figure 3.8) involved first casting a thin patch of Platinum Cure Silicone, which was then partially cured before embedding the natural fibers. Once set, these patches were adhered onto the smooth silicone surfaces. While this configuration enabled more accurate fur movement during inflation, prolonged interaction—particularly from children's repeated rubbing or squeezing—led to gradual shedding of the hair, indicating that durability remains a key challenge despite improved tactile realism. To support engagement and introduce rhythm awareness, each prototype was paired with a cartoon-style illustrated background panel. These panels displayed the animal's image alongside a simple annotation of its average breathing rate, guiding children to connect the visual cue with the tactile sensation of rhythm.

This phase prioritized scaling accuracy, tactile variety (fur vs. textured skin), and rhythm representation, offering a richer multisensory experience and setting the stage for comparative testing of children's perception and emotional response across species.

3.3.3 Structure of the Hair-Integrated Prototypes

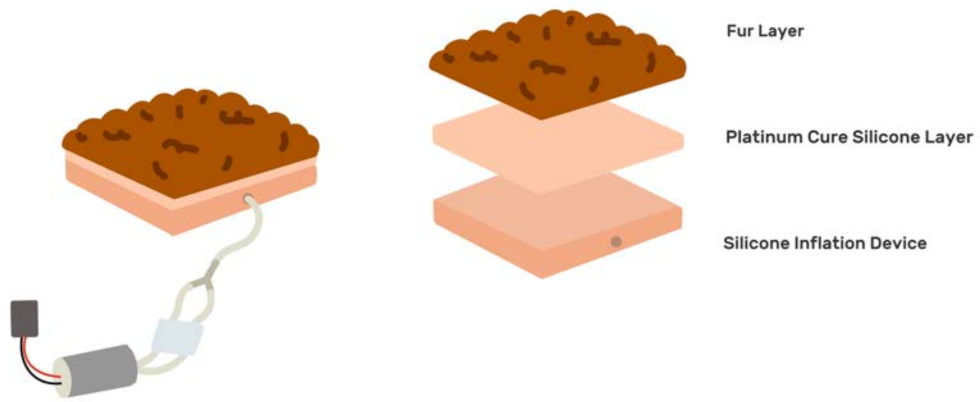


Figure 3.9 Structure of the Hair-Integrated Prototypes

In this iteration, each prototype was constructed with three main layers :

1. Fur Layer

The topmost layer represents the primary point of tactile interaction. For the llama and squirrel prototypes, this layer consisted of real animal fur provided by the zoo, delivering high sensory fidelity and emotional realism. The turtle prototype, by contrast, used a textured silicone surface that mimicked dry reptilian skin, derived from high-resolution 3D-printed molds. This variation supported the project' s goal of exposing children to different animal textures, from soft and fluffy to rough and rigid.

2. Platinum Cure Silicone Layer

Beneath the tactile surface, a thin layer of Platinum Cure Silicone was applied as an interface that provided elasticity, adhesion, and replaceability in a unified structure. Its flexibility allowed surface movement to synchronize smoothly with the inner inflation, while its strong adhesive properties ensured secure bonding with both fur and textured silicone layers. Additionally, this layer was designed to be replaceable, enabling maintenance or substitution without altering the internal mechanism. Its inherent softness also enhanced the illusion of "breathing," as the attached fur would lift and fall gently in response to rhythmic inflation.

3. Silicone Inflation Device

The innermost layer consists of a silicone inflation chamber. This layer is responsible for simulating the breathing rhythm by inflating and deflating in response to air pressure. The pneumatic system operates the inflation device, allowing the prototypes to expand and contract, mimicking the natural rhythm of an animal's breathing. This movement enhances the tactile experience, making it feel more lifelike and dynamic, contributing to the emotional engagement of the visitor.

Each of these layers works together to create an immersive and engaging tactile experience that closely mimics the textures and rhythms of real animals, enhancing emotional engagement and providing a multisensory interaction.

3.3.4 Display Design and Child Engagement

Following the completion of the three animal prototypes, the first public workshop was held on March 23, 2025, at Yumemigasaki Zoo's outdoor plaza (Figure 3.10). A 0.6 m × 1.4 m booth was arranged sequentially to support intuitive exploration and comparison: beginning with an introductory panel explaining the breathing simulation concept, followed by three prototypes aligned from left to right—turtle, llama, and squirrel—each placed before a cartoon-style illustrated background displaying their respective breathing frequencies (6-12 bpm, 15-25 bpm, and 60-80 bpm). The display concluded with two voting boxes prompting participants to choose "Which Prototype feels most like a real animal breathing?" and a suggestion pad inviting ideas for other animals to simulate.

This setup reflected a four-step interaction cycle—guidance, tactile exploration,

Figure 3.10 Public workshop setup at Yumemigasaki Zoo

voting, and feedback—which structured the educational experience. Facilitators played a key role in guiding the interaction by explaining the prototype mechanisms and encouraging exploration. Each Prototype was introduced by the facilitator, who explained its material construction: the turtle featured dry-textured skin created via high-resolution 3D-printed molds; the llama was covered with fleece sourced from the zoo's own animals; and the squirrel incorporated genuine short fur, providing a dense and fine tactile surface. The Prototypes were presented at a child-friendly height and spatially separated to allow for side-by-side interaction.

Children were encouraged to use both hands to press and feel the rhythmic inhale-exhale cycles, either comparing across prototypes or aligning the motion with their own breathing. Most visitors spent approximately five minutes at the booth, often arriving in family groups. Parents typically interacted first to demonstrate, after which children followed. This stepwise engagement helped ease children's initial hesitation—especially toward the movement of the prototypes—and enabled confident, independent interaction after just a short period.

Observations confirmed that the varying sizes of the Prototypes—15 cm for llama, 9 cm for turtle, and 3 cm for squirrel—successfully matched the perceived proportions of the real animals, aiding intuitive recognition. However, repeated interaction presented durability challenges: by the end of the session, the squirrel prototype's fur had largely detached, and the llama's fleece showed heavy wear, particularly due to children tugging or squeezing the surface vigorously.

These observations had a direct impact on subsequent design revisions. For example, repeated fur loss during tactile engagement highlighted the need for stronger fur attachment methods, which led to the adoption of needle-felting and layered adhesives in later prototypes. Additionally, frequent alignment of children' s own breathing rhythms with the prototypes revealed an unanticipated moment of embodied learning, reinforcing the emotional and physiological resonance of the system.

The inclusion of voting and suggestion mechanisms further amplified the participatory aspect of the exhibition. Out of 102 total votes cast, the squirrel received the highest count, followed by the llama and then the turtle. Open-ended responses included frequent mentions of monkeys, giraffes, penguins, elephants, and rabbits—highlighting species children found emotionally or physically compelling. This feedback informed both future animal selection and the storytelling direction of educational content.

Throughout the workshop, the embedded micro-pump system operated stably, with sanitization routines conducted between visitors to ensure hygiene. Overall, the deployment validated not only the tactile engagement potential of Prototype II in public settings, but also the educational value of a guided, multi-phase interaction flow that encourages emotional involvement and reflective feedback.

3.4. Prototype III -Improved Hair-Skin Integration Based on Field Feedback

Figure 3.11 Device construction details for turtle, llama, and squirrel prototypes

3.4.1 Motivation for Redesign and Durability Issues

During the first public workshop, while the tactile experience generated strong emotional engagement, a critical issue emerged: repeated interaction—particularly grasping and tugging by children—caused significant hair detachment on both the squirrel and llama prototypes. The fine short hair of the squirrel and the longer fleece of the llama exhibited visible wear by the end of the event.

These observations highlighted a key limitation in the initial attachment method, where fur was bonded directly onto adhesive silicone patches without reinforcement. The lack of structural anchoring meant that the tactile surfaces could not withstand sustained, high-frequency interaction typical of zoo settings, where children's behavior is often spontaneous and intense.

This durability issue not only compromised the immersive quality of the interaction but also limited the prototypes' lifespan, undermining their suitability for long-term public deployment. Given the project's emphasis on safety, realism, and repeatable engagement, addressing the attachment mechanism became critical for achieving both educational consistency and operational reliability in future applications.

3.4.2 Improved Hair Attachment Technique

In response to the identified issues, a revised fabrication process was implemented using a combination of needle felting, structural adhesives, and material layering (Figure 3.12). Real llama fleece and squirrel fur were first evenly spread across sponge bases and mechanically compressed into dense, fabric-like mats using traditional felting needles. This technique, rooted in wool-craft, created cohesive fiber sheets that maintained the authentic look and feel of real animal hair.

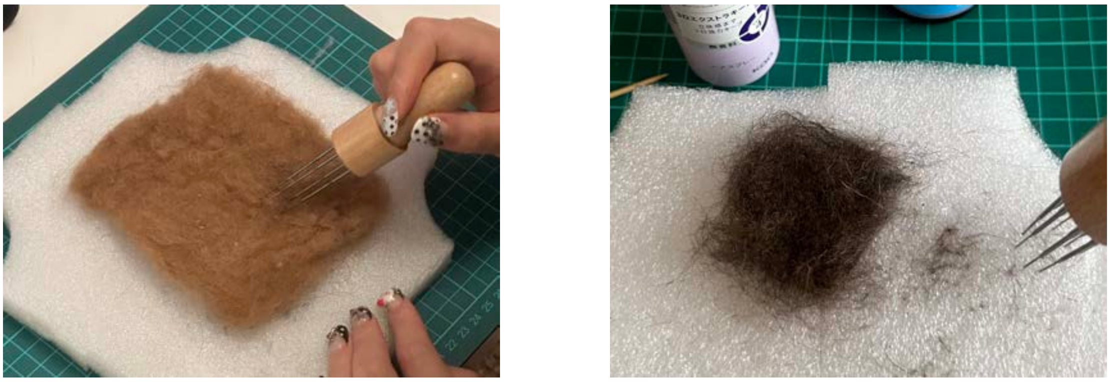


Figure 3.12 Improved hair attachment process using needle felting

To stabilize the fibers and reduce shedding, a hair-setting spray was applied uniformly across the surface. This felted hair layer was then bonded to a thin sheet of Platinum Cure Silicone, providing a soft yet adhesive interface. Additional adhesive was applied along all contact edges to ensure robust bonding between the layers.

This layered construction approach significantly improved both mechanical strength and surface realism. When applied to the llama and squirrel models, the new technique resulted in fur layers that remained intact throughout extended, high-frequency interaction—without compromising tactile quality.

3.4.3 Second Workshop Deployment

The upgraded prototypes were showcased during a second public workshop held on May 18, 2025, in the indoor rest area of Yumemigasaki Zoo. The booth setup mirrored the original layout: three prototypes were presented side by side, each with cartoon-style backgrounds indicating their respective breathing frequencies.

Figure 3.13 Second public workshop demonstrating upgraded tactile prototypes

Throughout the event, children were again encouraged to touch and compare the prototypes. However, unlike the first deployment, the improved fur layers sustained no visible damage despite frequent grasping and squeezing(Figure 3.13). The squirrel model in particular—previously the most fragile—remained intact after over two hours of continuous interaction.

Behavioral observations revealed that the improved durability contributed to longer and more confident interaction times. Several children returned to re-touch their preferred models after initial contact, indicating stronger engagement. Moreover, facilitators noted a drop in hesitation among younger participants, likely due to the smoother visual and tactile presentation of the improved surfaces.

This second deployment validated the effectiveness of the new attachment technique and demonstrated that a structurally reinforced, hair-integrated model can meet the demands of public educational use. The success of this iteration suggests the system is now suitable for sustained multisensory interaction in museums, classrooms, or zoo environments, where durability, hygiene, and emotional resonance are all critical.

3.5. Design Evolution and Insights

The three-stage prototyping journey marked a continuous refinement of both technical feasibility and user experience. Instead of a linear process, the design evolved through a cycle of field testing and feedback, gradually improving its educational value and emotional impact.

The initial elephant prototype (Prototype I) focused on simulating breathing rhythms and reproducing tactile skin textures. It served mainly as a technology demo. During the first meeting with staff at Yumemigasaki Zoo, the prototype sparked discussions about animal familiarity, emotional connection, and how well the design aligned with the zoo's educational goals.

Based on this input, Prototype II shifted toward a more context-sensitive approach. The team selected three animals from the zoo—llama, squirrel, and turtle—offering a range of breathing rhythms from fast to slow. This allowed children to compare different pulse speeds through direct touch. Fur textures were also adjusted based on staff advice, using real animal hair where possible. Cartoon-style panels showed the breathing frequencies to support age-appropriate learning.

During the first public workshop, it became clear that the squirrel and llama prototypes were not durable enough. Children's repeated pressing and pulling caused hair loss and surface damage. These problems highlighted the need for stronger materials that could withstand frequent use. In response, Prototype III introduced needle-felting techniques and improved bonding layers. These changes greatly increased the durability of the surface without sacrificing realism, and the upgrades were successfully tested at a second public event.

Throughout all stages, design decisions were informed by field observations rather than only lab-based testing. For example, children's initial hesitation, their preference for softer textures, and their tendency to synchronize their breathing with the models were all noted by facilitators and reflected in later changes. The process showed that it was not enough to simulate animal rhythms—the design also had to be approachable, safe, and easy to understand for young users.

In summary, the project gradually moved from a technical prototype to a durable, emotionally engaging educational tool. The close collaboration with zoo staff and real-world testing helped shape a more practical and meaningful design that can be adapted for broader public settings in the future.

Chapter 4
Evaluation

4.1. Evaluation Objectives and Method Overview

This chapter evaluates the effectiveness of the breathing simulator across three phases: a controlled indoor test and two field workshops conducted at Yumemigasaki Zoo. The primary objective was to assess the system's capacity to evoke tactile empathy through breathing simulation, while secondarily exploring its potential for educational engagement in public settings.

The indoor test focused on validating the perceptual clarity and emotional impact of the prototypes in a distraction-free environment. Conducted with university-aged participants (ages 20-35), it employed a structured 5-point Likert-scale questionnaire to evaluate five key metrics: breathing-rhythm perception, texture realism, emotional empathy, comfort/safety, and overall satisfaction. These quantitative measures provided a reliable benchmark for comparing the three animal prototypes—squirrel, llama, and turtle—under consistent conditions.

In contrast, the two public workshops introduced the prototypes into semi-structured, real-world zoo environments. Visitors included a wide age range, from young children and parents to seniors and international tourists. The first workshop used manual tally voting and open-ended comment pads to collect impressions, while the second employed color-coded dot stickers and QR-linked multilingual surveys to accommodate diverse users. Both events involved behavioral observation and verbal exchanges to capture spontaneous reactions and interactions.

This mixed-methods evaluation framework enables triangulation between laboratory-based performance and field-based resonance. By comparing indoor ratings with onsite behaviors and preferences, this chapter aims to extract design implications about how physical rhythm, material tactility, and contextual familiarity contribute to haptic empathy and user engagement.

4.2. Indoor Controlled Test

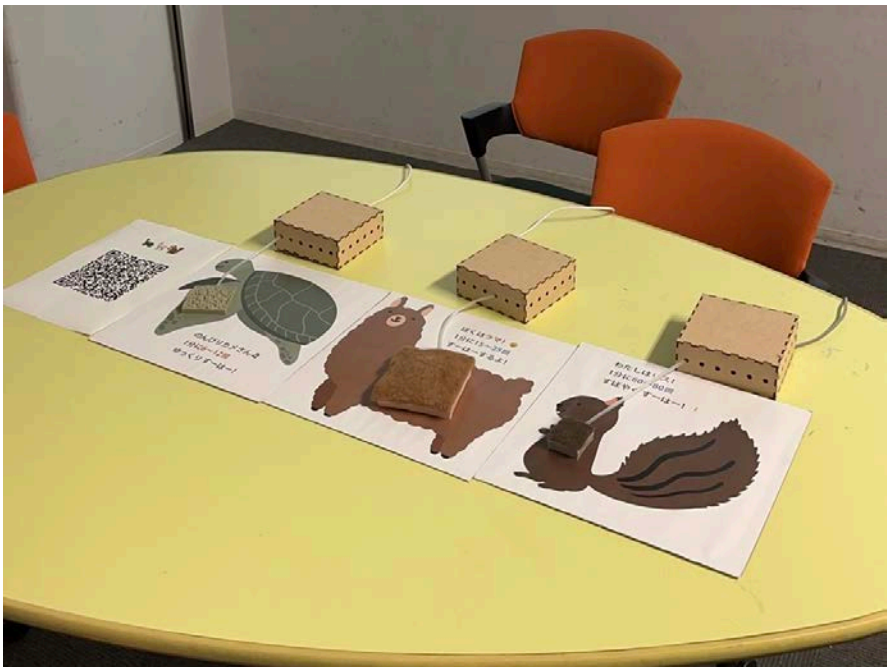


Figure 4.1 Controlled indoor user test session with animal prototypes

4.2.1 Objective

This evaluation aimed to verify whether the pneumatic silicone animal prototypes could effectively evoke emotional empathy and haptic engagement in a controlled indoor setting (Figure 4.1). It served as a baseline for comparison with public zoo workshop results. While the zoo-based workshops captured family and child interaction under real-world conditions, the indoor test offered a stable environment for systematically measuring user perception across multiple metrics.

4.2.2 Participants

A total of 14 adult participants (n=14) were recruited from a university campus, all of whom were fellow graduate students majoring in media design or related fields. The age distribution included six participants aged 20-24 and eight aged 25-35. Nine were female and five were male. Most participants reported visiting zoos once per year or less.

All participants had prior design experience, including coursework or projects involving tangible interaction, user experience, or physical prototyping. In addition, 11 out of 14 participants (78.6%) had hands-on experience with fine-touch practices such as pottery or embroidery. This background provided a relevant foundation for evaluating the tactile and emotional qualities of the breathing animal prototypes.

4.2.3 Procedure

Figure 4.2 Participants engaging with animal prototypes

The indoor test followed a structured procedure to ensure consistency across participants and enable comparative evaluation across prototypes. At the beginning of the session, the facilitator provided a brief overview of the research objectives and introduced the three animal prototypes—turtle, llama, and squirrel—highlighting their corresponding real-life breathing rates and the design rationale behind their tactile representations. Participants were then guided to interact with each prototype in a fixed sequence, using both hands to feel the rhythmic inhale-exhale motion, and were encouraged to compare the breathing rhythm with their own (Figure 4.2).

After completing the tactile experience, participants were introduced to the 5-point Likert scale used for evaluating the prototypes. The scale was explained as follows:

- 1 = Very poor/Not realistic at all/Not emotionally resonant/Uncomfortable/Very dissatisfied
- 2 = Poor/Somewhat unrealistic/Slightly emotionally resonant/Somewhat uncomfortable/Somewhat dissatisfied
- 3 = Average/Moderately realistic/Moderately emotionally resonant/Neutral/Moderate satisfaction
- 4 = Good/Realistic/Emotionally resonant/Comfortable/Satisfied
- 5 = Excellent/Very realistic/Strong emotional resonance/Very comfortable/Very satisfied

After understanding the scale, participants were asked to complete an online questionnaire accessible via QR code. The questionnaire included several sections. First, participants evaluated each prototype independently across five dimensions: perceived breathing rhythm, surface texture realism, emotional empathy, comfort/sense of safety, and overall satisfaction. These ratings were collected using the 5-point Likert scale, as previously explained.

In addition to these evaluations, participants were asked to provide a more detailed response about their preferences by selecting multiple reasons for choosing their favorite prototype. For example, participants were asked to indicate which aspects of the prototype—such as its breathing rhythm, texture realism, emotional empathy, or comfort—most contributed to their preference. This approach helped us understand the key factors influencing their choices and emotional engagement with the prototypes.

Furthermore, the questionnaire included questions aimed at gauging participants' future interest and engagement with the tactile breathing simulation experience. These included questions such as: How likely are you to return for another experience if this tactile breathing simulation device is exhibited long-term at the zoo? and How likely are you to recommend this experience to family or friends? Participants were also asked whether they would like to see breathing simulations for other animal species in the future, and if so, to specify which species. Any additional comments or suggestions for improvement were also welcomed to help refine the device for future use.

This combination of within-prototype ratings, across-prototype preferences, and additional engagement questions enabled both depth and contrast in assessing the prototypes' experiential impact. The responses provided valuable insights into not only the emotional and sensory impact of the prototypes but also the potential for long-term engagement, which is crucial for developing interactive exhibits for zoo visitors.

4.2.4 Per-Prototype Vertical Analysis

Each animal prototype squirrel, llama, and turtle was evaluated across five perceptual dimensions using 5-point Likert scales: breathing rhythm perception, texture realism, emotional empathy, comfort and safety, and overall satisfaction. The responses revealed prototype-specific strengths and highlighted the multidimensional effectiveness of the tactile breathing simulation. Each metric result is based on responses from n = 14 participants.

1. Squirrel Prototype

Participants largely perceived the squirrel prototype’s rhythmic motion as convincingly lifelike, with n = 13 (92.9%) rating it as “clearly” or “very clearly” resembling a real squirrel’s breathing pattern. The fur’s surface realism was likewise affirmed, though slightly less emphatically, with n = 10 (71.4%) rating it as “fairly” or “very” similar to real squirrel fur. In terms of emotional resonance, this prototype received the most positive feedback: n = 10 (71.4%) of participants strongly agreed that they felt emotionally connected to the squirrel' s life rhythm. The prototype was also praised for tactile comfort and safety, with n = 12 (85.7%) rating it as "somewhat" or "very" comfortable. Overall satisfaction was high, with all participants expressing some degree of satisfaction—n = 7 (50.0%) very satisfied, and n = 7 (50.0%) somewhat satisfied.

Table 4.1 Squirrel Prototype Ratings by Dimension (n = 14, Mean (SD))

Dimension	**Squirrel Prototype (Mean (SD))**
Breathing Rhythm	4.29 (0.61)
Texture Realism	3.93 (0.92)
Emotional Empathy	4.29 (0.47)
Comfort/Safety	4.14 (0.66)
Overall Satisfaction	4.50 (0.52)

The Squirrel prototype demonstrated a strong ability to evoke emotional engagement. The high emotional empathy rating (4.29) and comfort (4.14) suggest that both rhythmic realism and tactile softness contributed to a sense of lifelikeness and emotional resonance. The relatively high rating for texture realism (3.93) further supports the importance of fur authenticity in promoting sensory realism and affective engagement.

2. Llama Prototype

The llama prototype also performed strongly across all metrics. The breathing motion was judged realistic by n = 13 (92.9%) of participants. The fur-like texture, sourced from real zoo llamas, achieved a high realism score, with the majority (n = 11 (78.6%)) considering it closely representative of an actual llama' s coat. Emotional empathy scores were split evenly between "strongly agree" and "slightly agree," suggesting that the tactile feedback supported a rich yet somewhat subjective emotional response (n = 7 each, 50.0% / 50.0%). Comfort ratings were also strong, mirroring those of the squirrel prototype, with n = 13 (92.9%) reporting moderate to high comfort. In overall satisfaction, the llama slightly outperformed the squirrel, with n = 9 (64.3%) of participants rating their experience as "very satisfied."

Table 4.2 Llama Prototype Ratings by Dimension (n = 14, Mean (SD))

Dimension	**Llama Prototype (Mean (SD))**
Breathing Rhythm	4.29 (0.61)
Texture Realism	4.36 (0.63)
Emotional Empathy	4.29 (0.73)
Comfort/Safety	4.29 (0.61)
Overall Satisfaction	4.36 (0.50)

The Llama prototype achieved high ratings for both breathing rhythm and texture realism. Compared to the squirrel, the llama’s slightly higher realism score (4.36) may indicate that the longer fleece provided a more distinct tactile cue. While the emotional empathy score showed greater variation, overall satisfaction remained strong, supporting the design’s broad effectiveness.

3. Turtle Prototype

The turtle prototype showed more diverse responses. While n = 7 (50.0%) of participants found the breathing rhythm “clearly” or “very clearly” realistic, another n = 7 (50.0%) rated it only as “moderate” or “slight.” This may be attributed to the turtle’s inherently low breathing frequency and subtler expansion amplitude. However, texture realism received a solid endorsement, with n = 13 (92.9%) rating the dry, scaly surface as closely resembling a real turtle’s skin. Emotional empathy scored highest among the three prototypes, with n = 11 (78.6%) of participants strongly agreeing that they felt an emotional connection. Comfort perception was generally positive (n = 13, 92.9%), although slightly less intense than with the other two prototypes. Satisfaction scores skewed more toward moderate approval, with n = 10 (71.4%) “somewhat satisfied” and n = 2 (14.3%) “very satisfied.”

Table 4.3 Turtle Prototype Ratings by Dimension (n = 14, Mean (SD))

Dimension	**Turtle Prototype (Mean (SD))**
Breathing Rhythm	3.79 (0.70)
Texture Realism	3.57 (0.65)
Emotional Empathy	4.07 (0.47)
Comfort/Safety	3.79 (0.58)
Overall Satisfaction	4.00 (0.55)

Despite the turtle's more subtle breathing rhythm, its texture realism and emotional empathy scores remained strong. The contrast between moderate rhythm perception (3.79) and high emotional empathy (4.07) suggests that even low-intensity haptic stimuli can support engagement when paired with distinctive tactile surfaces.

4.2.5 Horizontal Preference Comparison

This section compares the overall ratings for the three prototypes—Squirrel, Llama, and Turtle—across five dimensions: breathing rhythm, texture realism, emotional empathy, comfort/safety, and overall satisfaction. The results are visualized in Figure 4.3, which summarizes the average scores and standard deviations for each prototype across all evaluation dimensions.

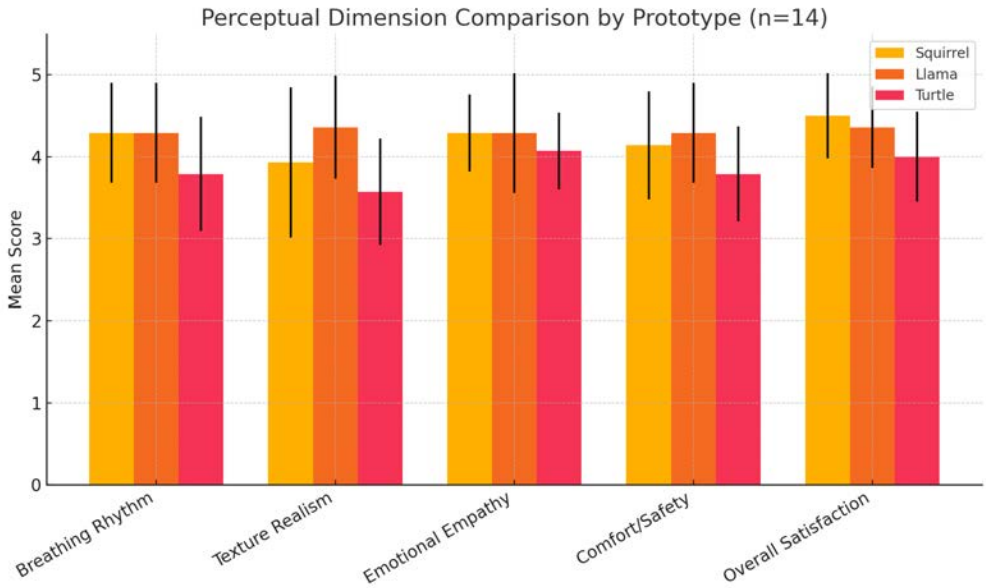


Figure 4.3 Comparison of user ratings across prototypes on five dimensions.

It shows that the squirrel and llama prototypes were rated similarly in breathing rhythm (M = 4.29), while the turtle prototype received a lower score (M = 3.79), likely due to its subtler motion. In texture realism, the llama prototype scored highest (M = 4.36), followed by the squirrel (M = 3.93), and turtle (M = 3.57). Emotional empathy ratings were comparable for squirrel and llama (M = 4.29), but the turtle prototype also performed well (M = 4.07), indicating that subtle motion combined with texture can still evoke emotional responses. Comfort/safety followed a similar trend, with squirrel and llama scoring above 4.0, and turtle slightly lower (M = 3.79). Overall satisfaction was highest for the squirrel prototype (M = 4.50), suggesting a well-balanced and emotionally engaging experience.

These findings highlight the value of combining real fur textures with clearly perceptible breathing rhythms to foster stronger emotional connections. The llama and squirrel prototypes, both incorporating zoo-sourced fur and pronounced breathing motion, received more consistent and high scores across most dimensions. The turtle prototype’s lower ratings in breathing rhythm—but still competitive emotional empathy scores—suggest that even subtle stimuli, when paired with realistic texture, can effectively engage users.

4.2.6 Future Interest and Engagement

In addition to evaluating the tactile qualities of the prototypes, the questionnaire gathered insights into participants' future interest and potential long-term engagement with the breathing simulation device. These questions were designed to assess the sustainability and scalability of the system within educational or exhibition settings.

When asked whether they would be willing to revisit the zoo if the breathing simulation device were permanently installed, 10 out of 14 participants (71.4%) responded "definitely" or "very likely." This indicates a strong level of future interest, highlighting the potential of the installation to encourage repeat visitation through emotionally resonant and memorable experiences.

Similarly, participants were asked if they would recommend the breathing simulation experience to friends or family. 11 out of 14 participants (78.6%) expressed clear willingness to promote the installation to others, suggesting promising word-of-mouth potential and broader public appeal.

Interest in experiencing breathing simulations of other animal species was also explored. Open-ended responses revealed enthusiasm for expanding the range of prototypes, with suggestions including elephants, lions, bears, and other iconic animals. This feedback reflects public curiosity about diverse and recognizable animal rhythms.

Finally, participants were invited to offer suggestions for improvement. Common themes included enhancing the realism of breathing in larger animals, adjusting the rhythm to feel more natural, and incorporating interactive elements such as gesture or proximity-based activation. These insights provide actionable directions for improving multisensory immersion in future iterations.

Overall, the results suggest that the prototype not only fosters immediate emotional engagement, but also demonstrates significant promise for sustainable educational use and long-term visitor retention.

4.3. Zoo Workshop I: Deployment and Feedback

4.3.1 Workshop Overview and Setup

The first public deployment of the tactile breathing simulator took place on March 23, 2025, at the outdoor plaza of Yumemigasaki Zoo from 10:00 AM to 3:00 PM. The setup featured a 0.6 m × 1.4 m table-based booth, designed to maximize accessibility and engagement. From left to right, the booth included:

- An introductory paper board, explaining the concept of the breathing simulator and the method of interaction.
- A turtle prototype (6‑12 bpm) made with 3D printed silicone, designed to simulate the realistic texture of turtle skin, and accompanied by a cartoon-style paper background illustrating its breathing rhythm.
- A llama prototype (15‑25 bpm) covered with zoo-provided llama's fur, providing a tactile experience based on real animal fur, and accompanied by a cartoon-style paper background showing its breathing rhythm.
- A squirrel prototype (60‑80 bpm) made with genuine fur, offering a highly tactile and emotionally resonant interaction, and accompanied by a cartoon-style paper background illustrating its breathing rhythm.

At the end of the booth, a voting board invited visitors to place tally marks under "Which prototype feels most like a real animal breathing?" The board was designed to encourage participants to engage with the prototypes and reflect on the level of realism they experienced. Alongside this, a suggestion pad collected free-written responses, including the question, "Which other animal would you like to feel?" This feature allowed visitors to share their thoughts on future expansions for the simulator.

Two facilitators supported the experience throughout the event: one provided explanations of the prototypes and interaction method, while the other guided participants through the tactile interaction and recorded voting results. The audience primarily consisted of families with children aged five to twelve, as well as individual or small-group elderly visitors. The atmosphere was informal and exploratory, fostering a mix of intergenerational interaction. Children were especially engaged, with many showing curiosity and excitement as they interacted with the prototypes. The low-pressure environment encouraged spontaneous exploration and allowed children and adults alike to express their thoughts and preferences freely.

4.3.2 Observed Behaviors and Interaction Patterns

Figure 4.4 Interaction patterns observed during the first workshop

Throughout the event, a wide range of interaction patterns were observed among children and their guardians. These behaviors can be roughly categorized into four typical patterns: "guided interaction," "autonomous exploration," "repeated immersion," and "investigative manipulation."

1. Guided Interaction: Some parents or grandparents first modeled how to touch the prototypes before encouraging children to try. This introductory approach helped hesitant participants feel safe and motivated to explore, especially in early stages of the event.

2. Autonomous Exploration: Many children approached the prototypes independently, especially when previous users were seen enjoying the experience. The soft silicone surface and rhythmic breathing movement triggered spontaneous interaction—most children used both hands to squeeze and press the prototypes, sometimes returning to their favorite animal multiple times (Figure 4.4).

3. Repeated Immersion: Children frequently re-engaged with the prototypes, often queuing up again after their first interaction. This cyclical behavior of "touch → explore → leave → return" showed a strong sense of emotional engagement and curiosity, particularly toward the squirrel and llama, whose textures and rhythm stood out.

4. Investigative Manipulation: Many participants flipped the prototypes, examined internal seams, twisted the fur, and attempted to identify the source of movement. One child even asked, "Where is the breathing?" These actions demonstrated a high level of cognitive and sensory immersion.

Notably, some children initially expressed reluctance—particularly when encountering the lifelike squirrel fur or the turtle's textured surface. However, after verbal encouragement or observing others, most of them gradually overcame their hesitation. Facilitators noted that tactile realism occasionally triggered emotional reactions ranging from curiosity to surprise. Several children even returned to touch the same prototype again after building confidence.

According to staff at Yumemigasaki Zoo, the prototype interaction was "easier to approach than real animals," and "soft textures made even nervous children reach out on their own." This aligns with observational data showing high levels of emotional openness during repeat interactions.

Moreover, some children compared the prototypes' motion to their own breathing after facilitators explained the concept of animal-specific rhythms. This prompted reflective thinking and self-awareness. Even shy or non-verbal children were seen gently touching and observing the breathing movement, highlighting the non-verbal inclusiveness of the design.

In summary, the workshop revealed a typical service flow from “encouraged initiation” to “tactile exploration,” followed by “repetition and comparison,” and ultimately, “emotional or reflective feedback.” This looped structure proved to be both developmentally accessible and emotionally impactful, especially for young visitors.

4.3.3 Tactile Accessibility and Emotional Engagement

Figure 4.5 Tactile interaction during the first workshop

The workshop demonstrated a high level of tactile accessibility across a wide age range. The exhibition layout was deliberately designed to match children’s eye level, with the prototypes placed on low tables and spaced to allow multi-user access. The soft silicone structure encouraged natural, hand-based interaction and minimized risk during extended tactile exploration(Figure 4.5).

Participants quickly grasped the concept of “breathing rhythms” without needing explicit instructions. Facilitators observed that the softness and lifelike motion naturally invited children to press, squeeze, and compare each prototype. Even first-time users intuitively distinguished among the different tactile and rhythmic profiles of the squirrel, llama, and turtle models.

Emotional responses were especially prominent among younger children. Several described the prototypes as “alive,” “soft like a pet,” or “like a sleepy animal.” One child commented, “This one breathes like me when I sleep,” referring to the mid-frequency llama prototype. These remarks illustrate how rhythmic motion enhanced the perceived presence of life and emotional connection.

While some children initially hesitated to touch more realistic features—such as the squirrel’s dense fur or the turtle’s rough texture—many overcame their reluctance after watching others or receiving gentle encouragement. This behavioral transition—from cautious observation to repeated engagement—demonstrated the emotional resonance of the tactile interaction.

Importantly, zookeepers noted that the non-verbal nature of the interaction was particularly effective for shy or younger children. One staff member remarked, “They didn’t need words—just one touch, and they stayed for a long time.” This form of embodied, sensory-based communication helped make the experience inclusive across different personality types and language abilities.

The rhythmic motion, especially in the llama prototype, fostered a calming yet vivid sense of life, which supported both emotional immersion and embodied learning. Children were observed placing their hands on their own chests and comparing their breathing with that of the prototypes, suggesting a moment of reflective self-awareness. These simple acts helped bridge physical sensation with internal states, offering a unique form of tactile empathy.

In summary, the workshop confirmed that breathing rhythm, combined with tactile realism, provides an accessible and emotionally engaging entry point for young audiences. The system succeeded in delivering a low-risk, high-impact sensory experience that encourages emotional bonding, personal reflection, and active participation—without requiring verbal explanation or adult mediation.

4.3.4 Voting and Feedback Summary

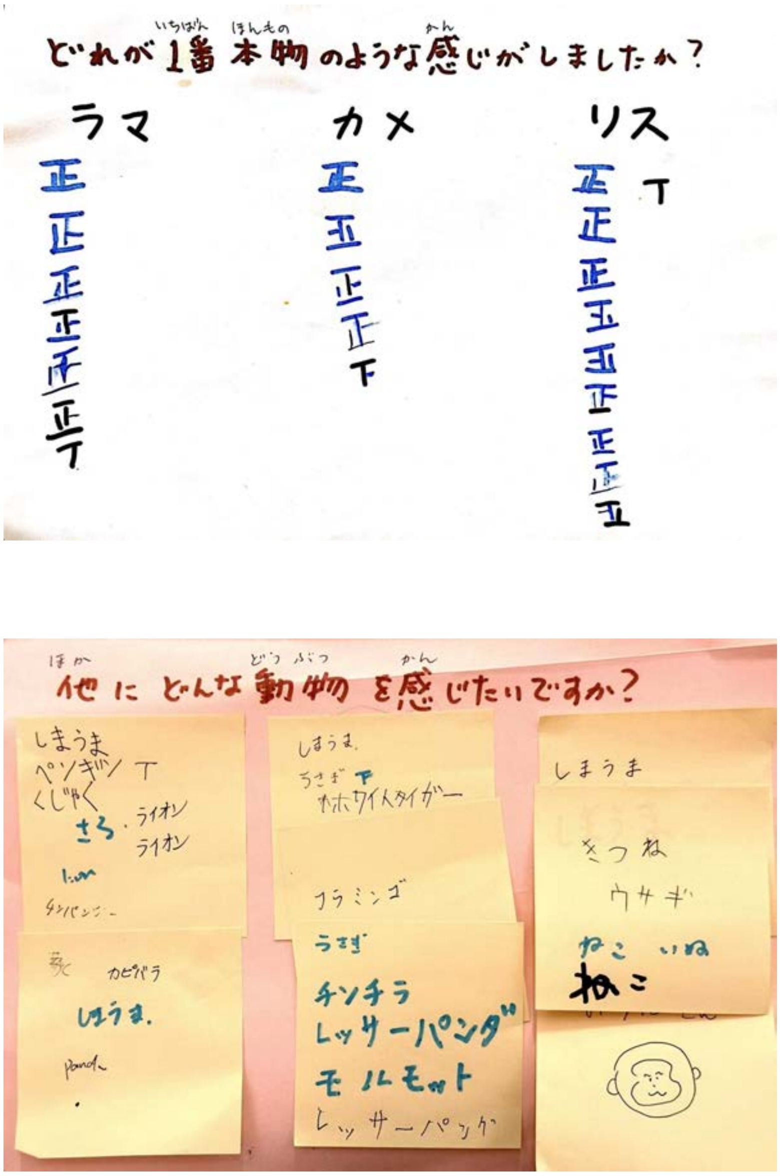


Figure 4.6 Participant voting results on perceived breathing realism of the three prototypes

By the end of the workshop, a total of 102 participants had cast their votes on the perceived breathing realism of the three prototypes. Each participant recorded their vote using tally marks under their preferred model, helping to gauge which prototype most effectively conveyed lifelike tactile breathing. (Figure 4.6).

The squirrel prototype received the highest number of votes (n = 45, 44.1%), followed by the llama (n = 35, 34.3%) and the turtle (n = 22, 21.6%). These results suggest that both breathing rhythm and surface texture realism strongly influenced perceptions of lifelikeness. The squirrel's pronounced rhythmic motion and real fur elicited particularly strong emotional responses, while the llama's soft fleece provided comfort and familiarity (Figure 4.6).

The turtle prototype, despite its textured realism, received fewer votes, likely due to its subtler breathing rhythm and less expressive movement. Several participants remarked that while the texture felt authentic, the lack of visible motion made it "feel less alive." This contrast indicates that rhythm dynamics are just as important as tactile fidelity in shaping emotional engagement.

In the open-ended suggestion area, participants were invited to propose animal species they would like to experience in future simulations. Frequent mentions included zebra, rabbit, monkey, and flamingo—animals that children found emotionally appealing, visually distinct, or familiar from previous zoo visits. These suggestions reflect a desire for diversity in tactile and rhythmic experiences, supporting future expansion of the system.

Participants also offered usability feedback, including suggestions for stronger rhythmic motion in some prototypes, enhanced tactile contrast, and the potential addition of sound or gesture-based interactivity. These insights point toward future directions for improving sensory integration and user engagement.

Throughout the event, the Arduino-based micro-pump system operated without interruption, and touchpoints were periodically disinfected between user groups to ensure hygiene. According to staff feedback, the tactile experience was "more acceptable and approachable than live animals" for some children, especially those hesitant to touch real fur. This highlights the accessibility and educational potential of the system.

Overall, the workshop validated the prototype's capacity to generate immersive tactile engagement and to serve as a compelling, non-verbal educational experience in real-world zoo settings. The integration of breathing simulation, realistic textures, and open-ended feedback illustrates the system's strong potential as an emotionally resonant, scalable exhibit.

4.4. Zoo Workshop II: Post-Improvement Verification

4.4.1 Workshop Overview and Setting

The second public workshop took place on May 18, 2025, inside the indoor rest area of Yumemigasaki Zoo, running from 10:00 AM to 3:00 PM. Approximately 120 visitors attended the workshop, with a primary audience of families with children aged 5‐12, along with elderly individuals and international tourists.

To accommodate the rising temperatures and ensure a more stable and hygienic interaction environment, the workshop was moved indoors. The layout remained consistent with the first workshop: the three prototypes turtle, llama, and squirrel were arranged from left to right, each displayed in front of cartoon-style paper backdrops illustrating their respective breathing rhythms (6‐12 bpm for the turtle, 15‐25 bpm for the llama, and 60‐80 bpm for the squirrel).

This consistent presentation allowed returning participants to recall their previous experiences, while offering first-time visitors an easy-to-navigate tactile experience.

To facilitate the voting process, colored dot stickers were used, simplifying the process and making it particularly accessible for younger visitors. The voting board featured two key questions: “Which prototype did you like the most?” and “Which prototype feels most like a real animal breathing?”, allowing participants to easily express their preferences.

In addition to the on-site voting board, a QR code linked to a multilingual online questionnaire was provided. This electronic questionnaire system aimed to collect more detailed and multi-dimensional feedback data, providing deeper insights for the research. By combining the simple, intuitive on-site voting system with the more detailed online survey, the workshop was able to meet the needs of participants across different age groups and gather comprehensive and rich user experience data.

Three team members coordinated the event: one facilitated the project background and interaction instructions, another guided tactile interaction and answered questions, while the third assisted with voting and survey completion.

The atmosphere remained informal and exploratory, fostering intergenerational interaction. Children were especially engaged, with many showing curiosity and excitement as they interacted with the prototypes. The low-pressure environment, coupled with staff guidance, promoted not only spontaneous exploration but also deeper reflection and verbal sharing from participants of all ages.

4.4.2 Observed Behaviors and Interaction Patterns

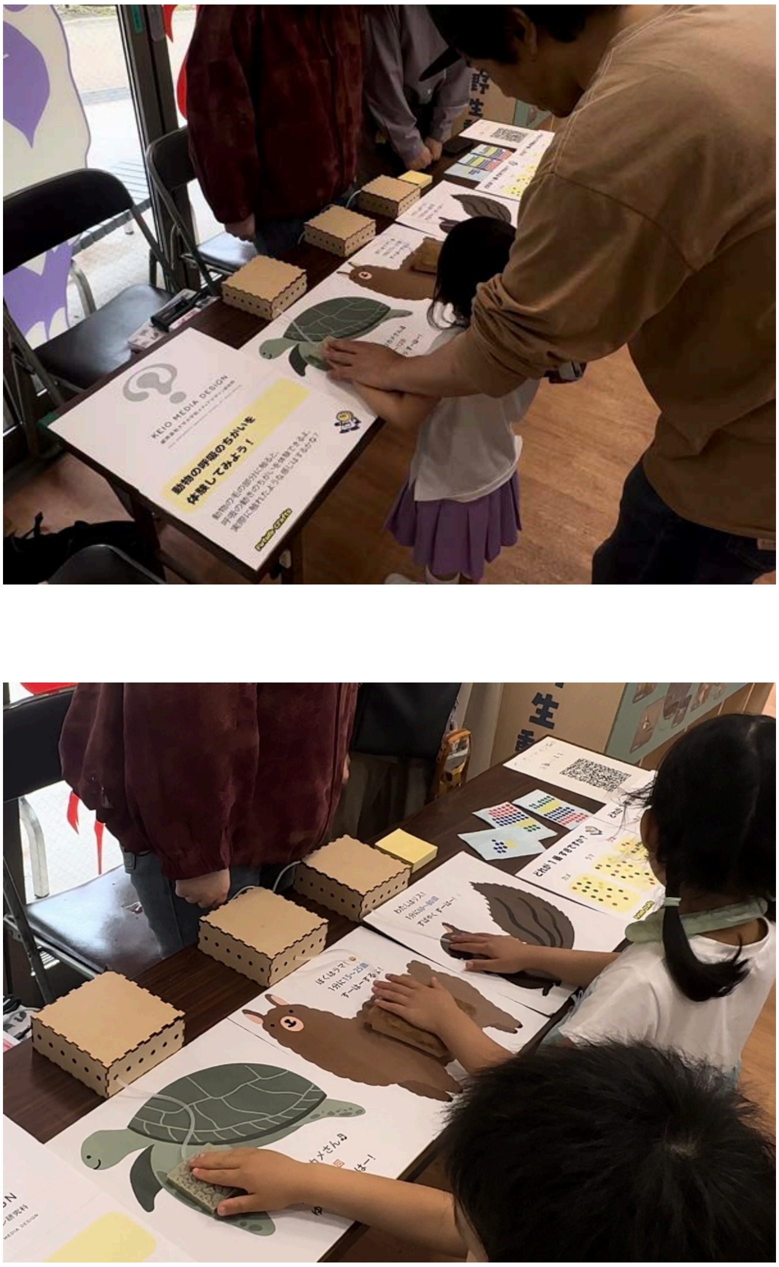


Figure 4.7 Visitor interactions during the second workshop

During the second workshop, a wide range of visitors including children, their guardians, and several senior and international guests engaged with the breathing prototypes. Children aged 5‑12 again showed the highest level of engagement, with most participants displaying immediate interest in the installations. The visible movement and soft textures of the prototypes prompted them to reach out and touch the surfaces without hesitation.

As in the first workshop, some children initially hesitated or showed fear upon seeing the breathing motion, particularly with the squirrel prototype's lifelike fur and the turtle's realistic scaly texture. The realism of these textures seemed to evoke a mix of fascination and mild apprehension. However, most overcame their hesitation after encouragement from guardians or staff, indicating a repeatable pattern of gradual tactile acceptance.

Several children later returned for repeat interactions, even waiting in line again to experience their favorite prototype. This demonstrated the emotional engagement and curiosity fostered by the tactile interaction.

Repeated observations revealed that children frequently used both hands to explore the inhale‑exhale cycles, pressing or poking the surfaces to test the feedback. A few especially curious children were seen flipping the prototypes over to investigate their mechanical operation, demonstrating not only tactile interest but also cognitive curiosity. These behaviors confirmed the simulator's strong capacity to capture attention and stimulate interaction across different age groups(Figure 4.7).

Notably, the durability of the revised fur attachment system was significantly improved. Throughout the five-hour session, no visible detachment occurred, even under frequent and vigorous handling by children. This contrasted with the first workshop, where signs of wear were present. The improved bonding and reinforcement techniques clearly enhanced the system's performance, allowing for reliable tactile engagement and maintaining the immersive quality of the interaction.

4.4.3 Tactile Accessibility and Emotional Engagement

Figure 4.8 Visitor interactions during the second workshop

The second workshop demonstrated high levels of tactile accessibility across a wide age range. The setup height was intentionally calibrated for children, ensuring easy access and encouraging natural hand-based interaction with the prototypes. The revised silicone skins and fur attachments—particularly the real llama and squirrel fur—elicited immediate tactile engagement, even among children with limited prior experience interacting with real animals(Figure 4.8).

Despite varying familiarity with animal textures, visitors quickly understood the concept of breathing rhythms and were able to identify distinct tactile characteristics among the three prototypes. Some children actively compared the motion of the prototypes to their own breathing, indicating a level of embodied awareness that deepened the interaction.

In comparison to the first workshop, where a broader range of age groups was involved, the second workshop' s indoor setting allowed for a more controlled environment, minimizing external distractions. This ensured that children, especially those aged 5‐12, could fully focus on the sensory experience. In both workshops, however, the non-verbal nature of the interaction played a key role in engaging children, particularly those who were initially hesitant or shy. The rhythmic breathing—particularly in prototypes like the llama with its mid-frequency pulses—helped foster a sense of life-like presence, making the experience deeply engaging.

Notably, several foreign visitors provided culturally grounded feedback. One group expressed that touching the llama prototype reminded them of llamas they had raised on a family farm, evoking a strong emotional memory. This cross-cultural resonance, reinforced by the use of real llama fur sourced directly from the zoo' s animals, created a deeper sense of authenticity and connection. Many visitors were visibly surprised and delighted upon learning this detail, which significantly enhanced their engagement.

A recurring observation was that children who initially hesitated—especially when encountering the squirrel' s dense fur or the turtle' s scaly surface—became more comfortable after verbal encouragement or demonstration by staff or guardians. Once engaged, many children remained at the station for extended periods or returned multiple times, underscoring the emotional pull of the interaction.

Compared to the first workshop, where children were more spontaneous and varied in their reactions, the second workshop' s setting allowed for more guided learning. Facilitators encouraged children to compare the breathing rhythms of the prototypes with their own breathing, helping them develop self-awareness and body-based empathy. This led to deeper engagement, particularly among the younger participants, further confirming the emotional impact of the interaction, which was both sensorially and emotionally resonant.

4.4.4 Voting and Feedback Summary

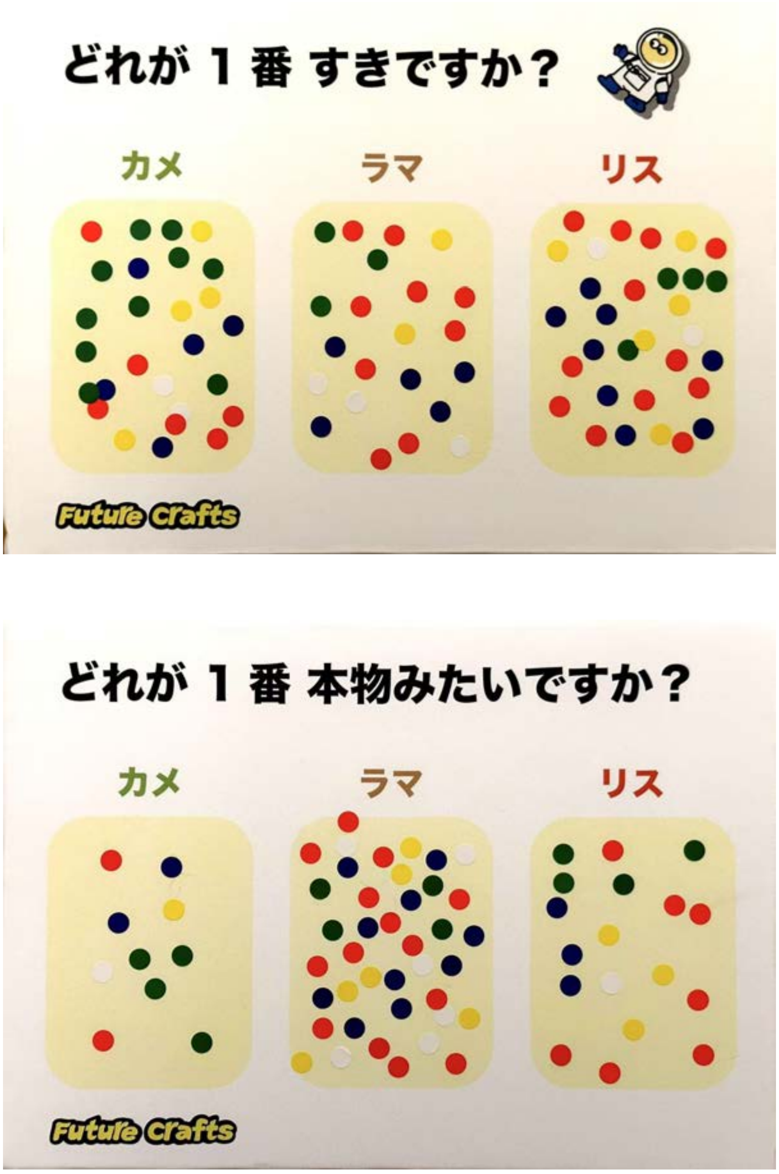


Figure 4.9 Second workshop voting results

A total of 80 participants cast votes for their “favorite prototype,” while 68 participants selected which prototype they felt had the “most realistic breathing.” The llama received the highest percentage of “most realistic” votes (n = 40, 58.8%), followed by the squirrel (n = 18, 26.5%) and the turtle (n = 10, 14.7%).

In contrast, the squirrel emerged as the favorite overall (n = 31, 38.8%), with the turtle close behind (n = 27, 33.8%), and the llama at (n = 22, 27.5%).

These voting trends reflect nuanced audience preferences shaped by both physiological fidelity and emotional appeal. Visitors who selected the llama prototype frequently cited the breathing rhythm' s moderate pace as being "most lifelike" and "realistically calm," especially when combined with the soft fleece texture. Notably, multiple international participants mentioned that the tactile experience resembled petting familiar animals from farms or zoos in their home countries. Several participants expressed pleasant surprise upon learning that the fleece was sourced directly from the zoo' s own animals, which heightened the sense of authenticity and emotional connection(Figure 4.9).

The turtle, while less frequently rated as "most realistic," attracted attention from those who appreciated its slow, deep rhythm. Many found it calming, likening the sensation to "touching a breathing pillow." Others, especially younger children, responded positively to the squirrel' s rapid pulsations, describing them as "cute" and "exciting." These varied responses highlight the strength of using multiple prototypes to represent a spectrum of animal breathing patterns, enabling participants to form personalized emotional connections.

In addition to the voting board, an online questionnaire was accessible via QR code. Twelve valid responses were collected (excluding test entries), and provided more detailed qualitative feedback regarding tactile perception, emotional engagement, and educational impact. Visitors consistently described the tactile experience using terms like "soft," "fluffy," "warm," and "gentle." These descriptors were especially common for prototypes with fleece or silicone textures mimicking real animals. Some participants noted that the sensation felt "kind" or "soothing," while others associated it with memories of petting zoos or personal animal experiences.

Feedback also revealed a strong awareness of differences in breathing rhythms. For example, participants noted that "the turtle' s breathing felt slow and relaxing," while "the squirrel' s fast pace was cute and exciting." These comments indicate that the rhythmic variations were not only noticeable, but also interpreted in relation to each animal' s perceived character. This suggests that the simulator successfully transformed invisible physiological cues into tangible, emotionally resonant experiences.

Participants were also asked whether the use of real animal fur enhanced the experience. Most responded positively, stating that the realistic textures contributed to a sense of authenticity. A few were neutral, but none reported negative reactions. When told that the fur came directly from the zoo' s own alpacas, several visitors expressed gratitude and surprise, noting that such detail added emotional weight and credibility to the interaction.

In summary, both sticker voting and qualitative feedback reveal a layered engagement profile: tactile familiarity fosters emotional openness, rhythmic variation supports cognitive reflection, and real animal materials enhance perceived authenticity. These factors combined to produce a meaningful, multisensory learning experience that resonated across age groups.

4.4.5 Technical Performance and Professional Reflections

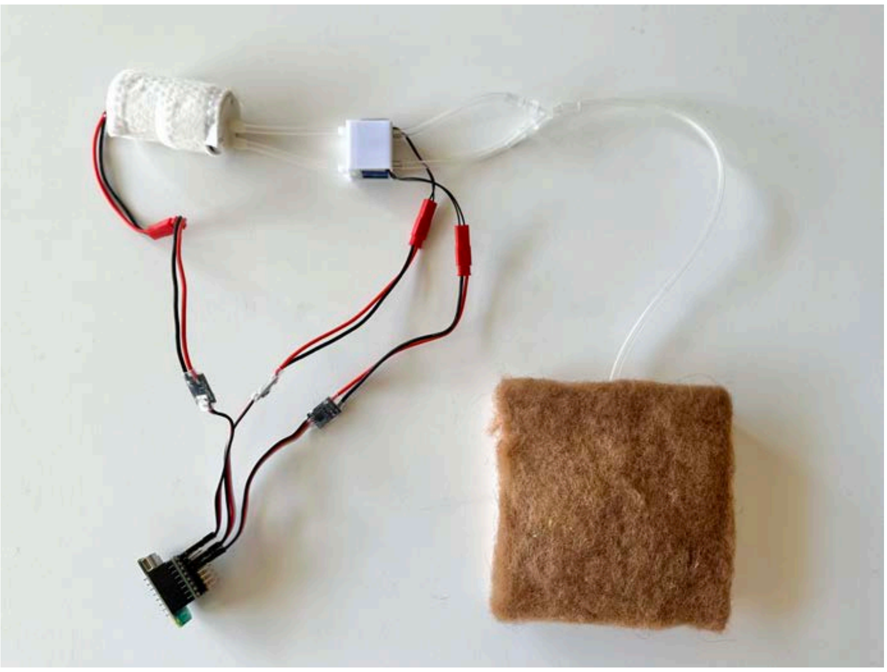


Figure 4.10 Overview of the complete prototype system

The second workshop reconfirmed the robustness and sensory impact of the revised prototypes. Compared to the first deployment, the upgraded fleece bonding and attachment system significantly improved durability. Although a few instances of minor fur detachment were still observed during prolonged use, these were rare and did not compromise the overall tactile experience. The micro-pump system maintained stable inhale-exhale rhythms throughout the five-hour session, and children engaged physically with enthusiasm, often comparing the breathing motion with their own using both hands. While several young visitors initially hesitated around the fast-pulsing squirrel, most became immersed following verbal encouragement(Figure 4.10).

Beyond visitor engagement, preliminary professional reflections were also gathered. A staff member from Yumemigasaki Zoo who observed the event commented that the llama prototype' s soft texture and natural rhythm offered a gentle introduction to animal behavior, especially beneficial for children unfamiliar or uncomfortable with live animals. The staff noted that such tactile surrogates could bridge the gap between curiosity and safety in educational settings.

Another zoo educator highlighted the emotionally inclusive quality of the prototypes, observing how the nonverbal interaction style enabled even shy children to engage through simple rhythmic touch. The tactile experience was seen as a valuable tool for lowering interaction barriers across diverse age groups.

In addition, an invited researcher specializing in tactile interaction design described the integration of real animal fur and breathing rhythm simulation as "a highly effective way to communicate unseen biological processes." They emphasized that the sensory experience combined physical realism with emotional resonance, opening up potential for broader educational use beyond the zoo—such as in classrooms or inclusive science exhibitions.

Alongside these positive evaluations, several constructive suggestions were raised. One expert pointed out that the location of the breathing motion could be made more anatomically precise—for example, by placing the inhale-exhale movement closer to the chest area, rather than being evenly distributed. Another suggestion involved the integration of thermal elements to simulate body warmth, which could enhance the realism of the interaction, especially when paired with soft fur textures. Such refinements were seen as the next step in evolving the prototypes from tactile curiosities to fully immersive educational tools.

Although informal, these reflections from both onsite staff and external experts offer early validation of the system' s educational and emotional design quality. They suggest that beyond entertainment or novelty, the breathing simulator holds promise as a serious medium for promoting haptic empathy and embodied learning in public-facing educational contexts.

4.5. Cross-Study Insights and Reflections

4.5.1 Summary of Key Findings

The combination of controlled indoor testing and zoo-based field deployment enabled a comprehensive, multi-perspective evaluation of the tactile breathing simulator. The indoor study, conducted under consistent lighting, sound, and time constraints, confirmed the simulator' s core effectiveness. All three prototypes received high scores across five key metrics—rhythm perception, texture realism, emotional empathy, comfort, and overall satisfaction—validating their perceptual clarity and emotional impact in focused conditions.

In contrast, the zoo workshops revealed the rich, unpredictable dynamics of public engagement, particularly among children. While many younger participants initially hesitated, especially with moving prototypes, the majority quickly showed enthusiasm and curiosity—often comparing breathing rhythms with their own or with siblings. The emotional connection appeared strongest when visitors realized that materials, such as llama fur, were sourced directly from the zoo's animals. These real-world reactions emphasized the prototype' s capacity to bridge tactile sensation with emotional resonance, highlighting that genuine materials like llama fur can significantly enhance perceived realism and engagement.

The emotional connection appeared strongest when visitors realized that materials, such as llama fleece, were sourced directly from the zoo' s animals. Several children and parents verbally expressed excitement upon discovering that the fur was not synthetic, stating it "felt more real." These real-world reactions emphasized the prototype' s capacity to bridge tactile sensation with emotional resonance, highlighting that genuine materials like llama fur can significantly enhance perceived realism and engagement, especially when they are linked to familiar animals from the local zoo.

In addition to visitor feedback, informal consultations were conducted with experts in animal education and haptic interaction design. These professionals confirmed the system's potential for fostering embodied learning and highlighted its suitability for non-verbal, cross-age educational contexts. They also suggested further improvements such as increasing the anatomical precision of breathing motion (e.g., shifting the movement closer to the chest or nostril area), and incorporating temperature feedback to simulate warm, living bodies. Their feedback added a valuable expert perspective to the user-driven evaluations and outlined clear directions for technical and experiential refinement.

4.5.2 Comparative Analysis

Controlled tests revealed that participants in the 20-35 age group could analytically distinguish texture and rhythm differences. The llama prototype was rated highest in texture realism and comfort, while the squirrel—despite its high-frequency rhythm—was favored for overall satisfaction, likely due to its engaging tempo and soft fur. These findings reinforce that a combination of rhythmic motion and texture realism are central to fostering emotional engagement and user satisfaction.

However, in zoo environments, a shift in preference was observed. In the first workshop, children were drawn to the fast-breathing squirrel, though its fur's fragility raised concerns. After technical refinements, the second workshop revealed a more balanced distribution: the llama emerged as the most realistic in terms of breathing rhythm, while the squirrel remained the most emotionally favored. These results suggest that realism and emotional appeal are driven by distinct qualities—rhythmic tempo and material familiarity, respectively—and that these effects vary by user group and context. This indicates that realistic texture, such as genuine fur, plays a key role in promoting emotional engagement.

4.5.3 Emotional Engagement and Learning Value

Repeated visitor feedback emphasized how touch-based exploration enhanced both curiosity and empathy. Some children expressed surprise at the slow breathing of the turtle or the rapid pace of the squirrel, while others found comfort in the softness and pulse of the llama. Many foreign visitors shared personal experiences of petting real animals and reported that the simulator evoked similar sensations. This reflects that tactile features, such as real animal fur, increase emotional resonance and familiarity, offering a more relatable and engaging experience.

Learning seemed to occur both through interaction and discovery, such as realizing that small animals breathe much faster or that "even a silicone turtle can feel calm." This indicates that even subtle variations in breathing rhythm paired with realistic textures can effectively trigger emotional resonance and engagement. The act of physically synchronizing with animal-like breathing rhythms—without verbal instruction—proved to be both intuitive and affectively rich, suggesting the potential of this method as a low-barrier, inclusive form of science communication that encourages embodied learning.

4.5.4 Practical Considerations and Future Deployment

Durability improvements played a critical role in second-stage success. The new felt-based fur adhesion sustained heavy interaction, and the module's stable pneumatic rhythm generated minimal disruption during prolonged use. However, maintenance considerations remain: silicone layers require regular sanitization, and the existing fur modules, which are already designed as replaceable units, should be supplemented with spare attachments. To support long-term deployment in zoo environments, we recommend preparing multiple backup hair components for each animal prototype to allow routine replacement during peak visitor seasons.

Additionally, sticker voting and multilingual QR-based surveys proved effective in gathering child-friendly and international feedback, pointing to best practices for future deployment. The simulator's low-power, low-noise design offers promise for semi-permanent zoo exhibits, especially where direct animal interaction is not possible.

Expert recommendations further support future upgrades to enhance biological realism and emotional engagement. Suggestions included adjusting the breathing movement’ s anatomical position—for instance, shifting motion to the chest or nostril area for certain animals—as well as incorporating subtle temperature feedback to simulate warmth. Such refinements would not only improve perceived realism but also strengthen the emotional and cognitive impact of the simulator in educational contexts.

Looking ahead, formal collaborations with haptics researchers and zoo educators are planned to conduct structured evaluations of the device’ s tactile fidelity and learning efficacy. These expert-driven assessments will complement public testing and inform future iterations aimed at broader deployment in science communication and informal education settings.

Chapter 5
Conclusion

5.1. Key Findings

Across three phases of empirical testing controlled indoor trials and two field workshops in a zoo setting the pneumatic silicone breathing simulator consistently demonstrated the ability to elicit tactile engagement and emotional empathy through rhythmic, non-contact interaction. Participants of all ages, from university students to children and elderly zoo visitors, responded positively to the synchronized inhale-exhale motions, validating the system' s effectiveness in delivering emotionally resonant experiences through non-verbal, tactile channels.

In the controlled indoor test, all three prototypes scored above 4.0 (on a 5-point scale) across five perceptual dimensions, confirming their clarity, realism, and emotional appeal under optimal conditions. The llama prototype emerged as the most realistic in terms of both texture and rhythm, with genuine fur significantly enhancing user perception. The squirrel prototype, with its dynamic frequency, was favored for its engaging tempo and emotional liveliness. These evaluations were echoed in participants'verbal comments, which emphasized the lifelike quality of movement and the emotional familiarity brought by authentic materials.

The first zoo workshop showed how haptic empathy extended beyond academic environments. Families with children enthusiastically interacted with the prototypes, often comparing the rhythms to their own breathing. Behavioral observations revealed that children lingered at the booth, touched and explored prototypes in groups, and returned multiple times. The squirrel prototype received the highest number of "most realistic" votes, reflecting its dynamic tactile presence.

In the second workshop, improvements to fur durability and interaction clarity enhanced engagement further. Participants expressed stronger emotional responses, particularly when informed that the animal fur used came directly from the zoo itself. The llama was praised for its calm and lifelike rhythm, the squirrel for its energy, and the turtle for its unexpectedly relaxing pace. Visitors of various backgrounds including foreign tourists highlighted the uniqueness and emotional value of the tactile experience. These results underscore the importance of material authenticity and rhythmic variation in evoking affective responses.

5.2. Significance

This study proposes a new design paradigm for zoo-based interaction: non-contact, rhythm-sensitive tactile exhibits that simulate animal breathing patterns using pneumatic silicone. Unlike traditional static displays or interactive zones that involve direct animal contact, the proposed system offers a multi-sensory and emotionally rich experience while upholding animal welfare standards.

From a design research perspective, this work contributes to the field of affective interaction by translating physiological rhythms specifically animal respiration into a tactile medium. The approach prioritizes temporal dynamics, such as inhale-exhale motion, rather than relying solely on static texture, thereby offering an innovative path toward embodied empathy through rhythmic touch. The successful calibration of breathing frequencies to match real animals, coupled with the use of genuine fur, illustrates how biological fidelity and material tactility work together to shape emotional perception.

Academically, the study intersects multiple disciplines: Human-Computer Interaction (HCI), design for learning, zoo education, and emotional interface design. It provides empirical evidence that breathing-based tactile stimuli, even in simple or low-tech forms, can generate meaningful emotional engagement. The combination of rigorous testing and public exhibition validates the system’s viability both in controlled environments and real-world settings.

Moreover, the design process including iterative prototyping, stakeholder input from zookeepers, and engagement with a diverse public audience demonstrates how participatory design can improve not only usability and durability but also emotional and educational impact. The simulator thus becomes more than a technical artifact; it functions as a design-led intervention aimed at reimagining zoo education in a post-contact era.

5.3. Limitations

While the study produced promising results, several limitations must be acknowledged.

First, the sample size in the controlled indoor trial was relatively small ($n = 14$) and skewed toward university-aged participants. While this group enabled consistent measurement, it does not fully represent the diversity of zoo visitors. Similarly, although the zoo workshops attracted a broad age range, data collection relied on observation and informal feedback, limiting statistical comparability across demographics.

Second, the study focused on three species turtle (6‐12 bpm), llama (15‐25 bpm), and squirrel (60‐80 bpm). While this provided clear contrasts in rhythm and texture, it did not encompass the full spectrum of animal respiration patterns. Future iterations could include species with extremely fast or slow rhythms, such as birds or marine mammals, to enrich the educational and sensory diversity.

Third, durability and hygiene remain concerns for prolonged deployment. Although the new felt-based fur attachment system improved resistance to wear, real fur modules are still susceptible to shedding over time. Regular maintenance, staff training, and spare module preparation are necessary, especially during high visitor seasons.

Fourth, field workshops were affected by uncontrolled environmental variables such as temperature, crowd noise, and foot traffic. While these conditions mirror real-life deployment, they complicate the interpretation of user reactions and may introduce confounding effects.

Lastly, the study did not evaluate long-term educational or behavioral outcomes. Although immediate emotional engagement was observed, it remains uncertain whether the experience contributes to lasting empathy or conservation awareness. Longitudinal studies involving follow-up surveys or return visitor analysis would be required to address this gap.

By addressing these limitations, future research can further strengthen the system’s robustness, scalability, and educational impact.

5.4. Future Directions

Building on the results of this study, several promising directions emerge for future development and interdisciplinary exploration. First, the simulator system can benefit from expanded multimodal integration. While the current design emphasizes tactile breathing rhythms, combining this with synchronized auditory cues—such as recorded animal breaths, ambient habitat sounds, or spoken narratives—could further enhance immersion and support layered learning. Visual augmentation, such as interactive AR overlays or mobile prompts, might also deepen engagement and help visitors draw connections between tactile sensation and biological facts.

Second, the system shows potential for application in therapeutic and rehabilitation contexts, especially for children with sensory processing challenges or individuals undergoing stress recovery. The slow, rhythmic motion and soft textures are consistent with sensory calming strategies, suggesting a possible role in mental wellness and emotional regulation. Collaborations with occupational therapists and psychologists could test and refine this use case.

Third, although the current prototypes are tabletop models for zoo settings, the underlying technology lends itself to wearable or personal-scale interaction formats. For example, a version of the device could be embedded in a plush toy, educational kit, or even a wearable belt that teaches about respiration through direct experience. This opens avenues for use in school science curricula, museum education kits, or at-home STEM learning.

Fourth, co-design with educators and animal care professionals should be prioritized in the next development phase. Structured workshops involving teachers, zoo staff, and learners can help identify optimal species, interaction formats, and interpretive content. In addition, feedback from zoo staff during this study highlighted practical suggestions such as enhancing anatomical realism by adjusting the location of the breathing motion, or adding a gentle warming function to better simulate body temperature which can inform the next iteration.

Fifth, longitudinal research is needed to measure whether tactile breathing experiences have lasting effects on empathy, knowledge retention, or conservation awareness. Future studies could deploy the simulator in multiple institutions, track return visits or quiz-based learning retention, and assess how engagement varies across cultures, age groups, and prior animal familiarity.

Finally, in terms of practical scalability, institutions would benefit from a modular toolkit that includes multiple animal presets, replaceable fur attachments, and a low-maintenance pneumatic control system. Maintaining realism while simplifying hygiene, storage, and repair processes will be critical for long-term deployment in high-traffic environments. Streamlining setup and cleaning procedures while maintaining safety and realism will be critical for adoption in busy public environments.

By pursuing these directions, the breathing simulator system has the potential to evolve into a widely applicable, emotionally resonant, and pedagogically effective platform for tactile learning in both formal and informal education settings.

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Appendices

A. Arduino Control Logic for Pneumatic Breathing Simulator

This appendix provides the complete Arduino control code used to drive the pneumatic breathing simulator. The code implements the breathing rhythm control for the llama prototype, managing inflation and deflation cycles through solenoid valves and a micro-vacuum pump.

Listing 1 Arduino control logic for pneumatic breathing simulator

```
const int INFLATE_VALVE_PIN = 2;
const int DEFLATE_VALVE_PIN = 3;
const int PUMP_ENABLE_PIN = 4;
const int ALPACA_INHALE_MS = 1500;
const int ALPACA_EXHALE_MS = 1500;

void setup() {
  pinMode(INFLATE_VALVE_PIN, OUTPUT);
  pinMode(DEFLATE_VALVE_PIN, OUTPUT);
  pinMode(PUMP_ENABLE_PIN, OUTPUT);
  digitalWrite(INFLATE_VALVE_PIN, LOW);
  digitalWrite(DEFLATE_VALVE_PIN, LOW);
  digitalWrite(PUMP_ENABLE_PIN, HIGH);
}

void loop() {
  // Inhale phase - deflate silicone chamber
```

```
  digitalWrite(INFLATE_VALVE_PIN, LOW);
  digitalWrite(DEFLATE_VALVE_PIN, HIGH);
  delay(ALPACA_INHALE_MS);

  // Exhale phase - inflate silicone chamber
  digitalWrite(DEFLATE_VALVE_PIN, LOW);
  digitalWrite(INFLATE_VALVE_PIN, HIGH);
  delay(ALPACA_EXHALE_MS);

  // Brief pause between breathing cycles
  digitalWrite(INFLATE_VALVE_PIN, LOW);
  digitalWrite(DEFLATE_VALVE_PIN, LOW);
  delay(500);
}
```

The control logic operates on a simple state machine with three phases: inhale (deflation), exhale (inflation), and a brief pause. Pin assignments correspond to the solenoid valve connections, with the pump maintaining constant operation throughout the breathing cycle. The timing constants can be adjusted to simulate different animal species' breathing rates.