BearBubbles: Interactive Olfactory Enrichment to Encourage Foraging in Zoo Animals

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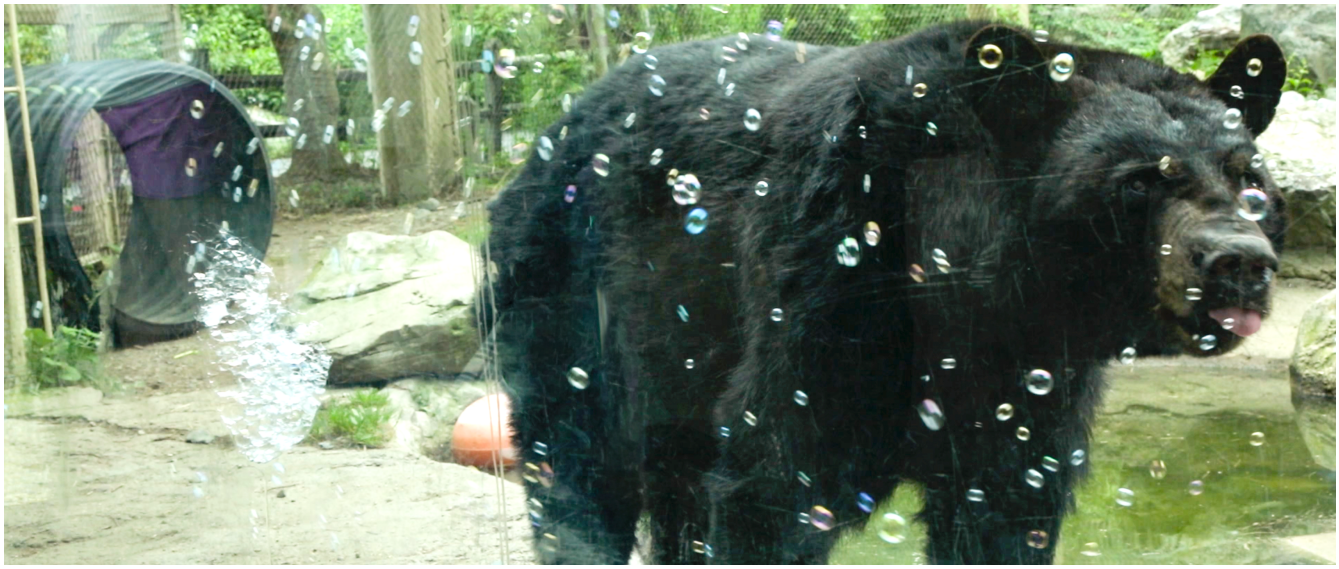


Figure 1: Zoo-housed black bear Bubba engages with scented bubbles during BearBubbles enrichment. Proximity-triggered bubbles with distinct scents across zones elicited natural behaviors (sniffing, licking, pawing, etc.), with increased agency

Abstract

Enrichment is critical for zoo animal welfare. Commonly used food-based approaches have limitations in terms of sensory diversity, agency, redundancy, time budget, and nutrition. Building on research into agency-based technologies, choice-driven enrichment, and species relevant sensory engagement, we developed an interactive proximity activated scented bubble system for two American black bears (*Ursus americanus*). This project integrates behavioral intervention with HCI methodology to create animal-controlled olfactory enrichment. Over a three-week deployment, we assessed (1) enrichment potential through system use, behavioral diversity, and habitat use; (2) usership via engagement patterns with the bubbles; (3) sense-making and agency through anticipation behaviors; and (4) human stakeholder perspectives via visitor and staff surveys. Results show the intervention increased target foraging and locomotive behaviors compared to post-feeding baselines, generated rich multi-modal interactions, and received positive stakeholder feedback, illustrating how technology can promote animal agency while supporting zoo welfare and educational missions.



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CCS Concepts

• **Human-centered computing** → Empirical studies in interaction design; *Gestural input*; *User centered design*.

Keywords

Animal-Computer Interaction, Animal Technology, Zoo, Animal Enrichment, Bear, Bubble, Agency-based Enrichment, Olfactory Interfaces, Foraging

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1 Introduction

Bubba and Smoky are two black bears *(Ursus americanus)* who have lived together at Zoo New England's Stone Zoo in Stoneham, MA for nearly two decades since being rescued as cubs. Deemed too habituated to humans for release, they now serve as "ambassador animals" for conservation education. As geriatric bears, they face age-related challenges (including arthritis and declining activity, and weight management concerns despite being highly food motivated) that complicate traditional food-based enrichment. Their needs reflect a broader challenge in zoo care: how to provide meaningful stimulation for aging animals whose needs extend beyond conventional approaches.

1.1 Zoo Enrichment: Evolution and Limitations

Environmental enrichment has evolved significantly since Shepherdson's foundational work [85] and is now mandated for all Association of Zoos and Aquariums (AZA) accredited zoos. Effective enrichment introduces activities or stimuli that promote species-appropriate natural behaviors, reduce stress and stereotypies, and increase animals' agency and behavioral diversity [11, 65]. For bears, these goals pose distinct challenges. Wild black bears can forage for up to 18 hours daily [15] and rely heavily on olfaction, yet in managed care are prone to developing abnormal behaviors [15]. Longer zoo lifespans [87] also introduce age-related needs [52]. Specifically, older bears require approaches to avoid overfeeding while promoting gentle physical activity. Food-based interventions are labor-intensive to prepare, limited by dietary constraints and weight-management concerns, and often do not achieve the prolonged foraging patterns desired. Prior work indicates that enrichment is most successful when it leverages animals' dominant sensory modalities while supporting choice and control [46, 90]. For bears, agency-driven olfactory enrichment can extend foraging-like engagement and support autonomy, with increased choice shown to improve psychological welfare in zoo settings [25, 81]. Curated choice and environmental challenge can develop autonomy in zoo settings [81], with increased choice improving psychological welfare [25]. These limitations and context highlight the potential for interactive, sustainable, and multi-sensory technology-mediated solutions that could address current enrichment constraints while providing bears with more engaging, agency-based, and species-appropriate experiences.

1.2 Technology-Mediated Animal Enrichment

In recent years, Human-Computer Interaction (HCI) and the subfield of Animal-Computer Interaction (ACI) have explored how interactive systems can support non-human animals as users [20, 47, 57]. ACI emphasizes species-specific perception and behavior, and uses behavioral evidence to assess engagement and welfare [58, 69]. Researchers have developed a range of tools to support animals' well-being by responding to their perceptual, behavioral, and ecological characteristics through agency-driven interactive engagement [31, 70, 80]. These include tablet based games for cats [70, 73], physical button interface design for dogs [80], or robotic navigation system for fish [31].

Technology-mediated enrichment offers several key advantages: real-time response to animals [50]; multi-sensory technology catering to their unique perception [53]; user-centered design methodologies tailored to specific species needs; sustained engagement with reduced Zookeeper intervention [64]; and individualized adjustment over time. Prior work demonstrates that animals can benefit from interactive, agency-driven systems, including touchscreen interfaces for primates [94], movement-based music systems for elephants [61, 99], underwater toys for seals [22], and control interfaces for macaws [50]. However, bears remain largely underrepresented, and olfactory interfaces comprise only 1% of ACI research [47] despite the centrality of smell for many species. Meanwhile, HCI has deep foundations in olfactory interface design for human users [56, 67, 77, 98, 100], yet these systems have rarely been adapted for animal users or for low-intrusion, outside-habitat deployment (critical in species where enrichment objects must withstand high physical force and are easily destroyed).

Zoo enrichment is also an inherently human problem: because humans create, deploy, and maintain the systems that shape zoo animals' daily experiences, enrichment technologies must balance the needs of *three* stakeholder groups. Following established ACI framings of human-animal-technology relations [57], zoo-based systems necessarily involve (1) the animal users, (2) the human facilitators who operate and maintain the system (Zookeepers), and (3) the human observers whose perceptions, empathy, and learning are shaped by the exhibit (visitors). Designing for this multi-species setting requires systems that are legible, durable, and safe for animals; simple and low-burden for keepers; and free from negative impacts or misunderstandings for visitors.

1.3 BearBubbles: A Proximity-Activated Olfactory System

Collaborating with Stone Zoo's animal enrichment and well-being team, we developed BearBubbles to address these challenges. Following AZA best practices for behavior-based enrichment, the system aimed to promote natural behaviors of locomotion and foraging, while countering excessive resting behavior. To meet these needs, we defined the following design considerations: (1) *non-food based* to avoid over-reliance on food rewards, important for weight management; (2) *olfactory* to align with bears' strong smell capabilities; (3) promotion of locomotion and foraging behaviors while countering excessive resting; (4) bear-controlled activation; and (5) built-in ethical safeguards such as cool-down periods.

Scented bubbles emerged as a promising medium, offering olfactory cues with visually interesting, unpredictable dispersal. Prior bubble interventions (generally unscented and non-interactive) have shown benefits for seals [41], trout [45], and dogs [40]. Unlike traditional scent enrichment, which requires scented items *in* the habitat with sustained Zookeeper intervention, our system differs by enabling proximity-triggered, bear-controlled activation from outside the habitat, creating ongoing, self-paced opportunities for engagement as scents disperse in wind.

BearBubbles extends ACI by introducing a proximity-activated olfactory interface tailored to black bear behavioral ecology and sensory priorities, and contributes to HCI research exploring interactive technologies extended to more-than-human contexts. Our study also offers insight into multi-species environments (visitors, Zookeepers, and animals), where new technology can affect *both* the human and animal stakeholders as well as their mutual interactions [18]. Four research questions guided our investigation:

- **RQ1:** Does the system provide positive enrichment for the bears measured in terms of behavior, habitat utilization, continuity of use, and system activation?
- **RQ2:** What forms of bear usership emerge in terms of interaction styles and their changes across bears, scents, and time?
- **RQ3:** Do the bears exhibit show evidence of sense-making about their agency over the system?
- **RQ4:** How does the new enrichment impact human stakeholders' perceptions of the bears and zoo enrichment?

Our findings show that BearBubbles successfully increased foraging behaviors and locomotion during deployment sessions compared to post-eating baselines. Visitor and zoo staff surveys responses indicated meaningful exhibit experiences and positive professional opinions of the system.

2 HCI & ACI Contributions

Our primary contribution is BearBubbles, a proximity-activated olfactory enrichment system that integrates behavior-based welfare goals with HCI and ACI methodologies. As a species-tailored, scent-based, non-food enrichment tool requiring minimal keeper intervention, BearBubbles demonstrates how user-centered design can address practical welfare challenges while broadening the scope of interactive systems to non-human users and inter-species contexts. The work advances Animal-Computer Interaction for an underrepresented species, through species-specific sensory design, durable and low-intrusion deployment, and support for animal agency via self-initiated activation.

BearBubbles also contributes to HCI by examining enrichment technology within a *multi-species* environment in which animals, visitors, and Zookeepers interact around a shared technological system. Because zoo enrichment is ultimately a human responsibility (shaped by the tools we build to care for animals), our work shows how interactive systems can support Zookeeper workflows, offering a low-maintenance, recalibratable enrichment tool that aligns with ongoing care practices. At the same time, we evaluate the system's impact on visitors, demonstrating that an artificial, technology-mediated enrichment does *not* diminish visitor empathy, welfare awareness, or conservation-oriented educational outcomes. By assessing both Keeper-facing utility, animal behavior, and visitor-facing perception, this research illustrates how enrichment technologies can simultaneously advance animal welfare and preserve human-centered educational mission of zoos.

3 Related Work

Enrichment is required at AZA-accredited zoos to promote behavioral diversity and physical and mental health, mirroring wild activity patterns [4]. Recent animal technology research contributes to these goals through interactive, species-specific systems. We situate our work in more-than-human HCI, focusing on technological, olfactory, and bubble-based enrichment, as well as olfactory interfaces in HCI.

3.1 Human and Animal Computer Interactions

Within HCI, animals are increasingly recognized as users rather than passive subjects of technology. ACI investigates how interactive systems can be designed around animals' sensory, cognitive, and ecological characteristics rather than for human-centered goals [57]. Across pets [49, 80], working animals [13, 43], farms [35], laboratories [31], wildlife [28], and zoos, researchers have created technologies supporting welfare, training, monitoring, or enrichment. Positioning animals as users aligns with welfare principles of good feeding, good housing, good health, and appropriate behavior [14] by creating enrichment that offer choice and the opportunity to perform species-typical behaviors. A recent HCI paper presenting a scoping review of 800+ animal technology papers found zoo and aquarium contexts comprise 15% of animal-technology work, and that olfactory systems remain rare ($\approx$ 1%) [47], highlighting both interest in zoo technology in HCI and underexplored potential for scent-based interaction. The review also showed that zoos most consistently position animals as technology users: 55% of projects met all criteria for usership (sensory feedback, animal beneficiaries, empirical testing). In contrast, laboratory, farm, or wildlife contexts often treated animals as research subjects without providing control, feedback, or sense-making potential. These findings suggest zoos are well-suited for extending user-centered methods to animals by prioritizing their needs and perception. Zoo studies also highlight multi-stakeholder dynamics: 70% emphasized animal benefit while 78% noted human benefits such as education, empathy, or improved working conditions. These patterns underscore zoos as key multi-species sites for user-centered interactive design benefiting both animals and humans as stakeholders.

3.2 Enrichment in Zoos

3.2.1 Technological Enrichment. Zoos provide structured contexts for testing interactive enrichment because they balance husbandry routines with novel interactions. Building on Markowitz's early animal-controlled devices [59], recent systems include touchscreen or projections for primates [60, 75], trunk-activated sound systems for elephants [29, 61, 99], sensor-based audio devices for lemurs [94], hanging feeding balls for giraffes [32], physically controlled music interfaces for parrots [50], or instrumented toys and projection games for sea otters [78]. Recent collaborative works at Stone Zoo

explored non-food-based, agency-oriented acoustic [34] and mirror-based systems [44] enrichment for primates, as well as puzzle-based enrichment for arctic foxes [64]. Evaluations typically employ camera monitoring, focused on system engagement [32, 61, 78, 99], and sometimes instrumented toys [78], or wearable monitors [12]. Some assess behavioral changes beyond engagement [50, 94], often triangulated with Zookeeper observations, but rarely combine full behavioral analysis with HCI usership methodology.

Despite this growing research of zoo-focused ACI work, cognitive-testing literature on bears [5–7, 91–93, 103], and bear-monitoring technologies [9], enrichment-focused ACI for bears remains limited. Examples include computerized testing for sun bears [74] and proposed (albeit untested) welfare-monitoring systems [12]. This gap highlights opportunities for enrichment grounded in species-typical behaviors.

3.2.2 Olfactory Enrichment. Scent-based enrichment is fairly common in zoos and has been used to encourage foraging [33] or locomotion [27] and to reduce stress [89]. Studies report increased foraging in Javan gibbons (*Hylobates moloch*) [33], reduced stress indicators in primates with essential oils [89], and shifts in space use in Rothschild giraffes (*Giraffa camelopardalis*) in an attempt to maximize time near the scent dispersal point [27]. Prior work has shown that scent can stimualte activity and reduce stereotypy when preferred scents are used [94] but often produces short-lived effects and habituation risks [17, 96]. Recent work across taxa, including meerkats [66], lemurs [8], and primates [89], emphasizes the need for species-specific evaluation [24]. This project contributes to the broader discussion on olfactory enrichment in zoos.

3.2.3 Bubble Enrichment. Bubble enrichment has been formally explored primarily in aquariums, where underwater bubbles reduce abnormal swimming patterns in seals [41] and support positive feed anticipation in rainbow trout [45]. For terrestrial animals, bubble machines were shown to reduce stress behaviors in domestic canines undergoing training [40]. To the best of our knowledge, no work has examined bubbles as enrichment for bears, but Stone Zoo had previously tested high powered bubble machines with the black bear users in the past.

3.3 Olfactory Interfaces

HCI researchers and artists have long explored ways of incorporating olfaction into interactive systems, primarily for immersion and communication [37, 39, 56, 67, 77, 98, 100]. Typical approaches deliver scents by diffusing vapors [79, 101], heating scented solids or liquids [19, 21, 54], or aerosolizing fragrant solutions [1, 10]. Once produced, the odorized air is directed toward the user via airflow, vortices [101], or even ultrasound arrays [38]. Seah et al.'s *SensaBubble* is closest in form to our approach, though it used bubbles filled with fragrant fog as a transient human-facing display doubling as a projection surface [83]. Our system instead uses scented bubble films as lightweight odor carriers drifting into the habitat. Few olfactory interfaces have been deployed with animals; a notable exception is *SensorySafari* for red-ruffed lemurs (*Varecia rubra*) [94], which delivered scents by passing air over dried fruits and flowers. Our work extends these ideas through a deployable, interactive, zoo-ready olfactory system.

3.4 Black Bears (*Ursus Americanus*)

Native to North America, American black bears inhabit a wide variety of ecological habitats [68, 86]. As opportunistic omnivores, they use their highly attuned olfactory abilities to locate diverse food sources and navigate their environment [97]. In fact, bears are thought to have one of the strongest senses of smell of any mammal, with black bears reported to detect scents across distances ranging from two to twenty miles depending on the source [84]. This exceptional olfactory acuity makes scent especially relevant to both ecological and human care contexts.

Given this sensory profile, olfactory enrichment is a particularly meaningful component of black bear care. Zoos employ a range of scent-based approaches (from natural and artificial scents to scented physical objects [17]) selected according to enrichment goals and individual animals. However, enrichment for black bears has primarily centered on food-based options, including honey filled logs [15], automatic feeders [16], and various physical feeders to increase novelty [71]. Beyond food, interventions such as providing access to larger or more complex spaces [11] or introducing natural and environmentally relevant scents [104] have been explored to reduce pacing and increase foraging behaviors.

4 System Design

The BearBubbles system (see Figure 2) was designed to deliver olfactory enrichment through proximity-based activation. When bears enter designated sensor zones, the system releases scented bubbles into the habitat. The design emphasized bear-control, welfare and safety. The resulting system is cost-effective, weatherproof and easy-to-setup. We provide implementation resources online.[1]

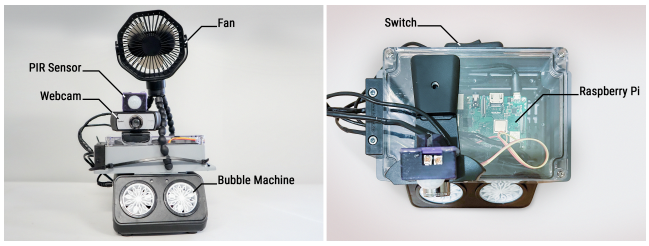


Figure 2: BearBubbles system. Left: Front view showing the fan, PIR sensor, webcam, and bubble machine. Right: Top view of the external on/off switch and the water-resistant housing containing the micro-controller.

4.1 Design Considerations

The system was designed around the specific needs of the two geriatric black bears. A core principle was to provide olfactory enrichment without food rewards, reducing risks of overfeeding while still leveraging the bears' strong food motivation. Accordingly, bubble scents were selected to resemble favored food items, but deployments occurred after the morning feeding to hopefully sustain exploratory behavior beyond mealtime. The three final scents were chosen in consultation with zoo staff, aligning with existing enrichment practices.

[1] https://www.interactanimallab.com/projects/bearbubbles

Animal agency was another key consideration. The proximity-based activation, allowed the bears to trigger enrichment through their own movements rather than having it imposed. While the causal link with bubble release might not be immediately apparent, zoo staff anticipated the bears could develop some sense of this connection over time. Based on previous work and expert feedback, further complexity from this direct literal mapping could have risked reducing animal sense-making.

To mitigate habituation, the system was designed with multiple scent modules that could be swapped or rotated, along with repositionable trigger zones to introduce novelty and variation across sessions. The physical behavior of the bubbles shaped by wind patterns was also considered a source of environmental unpredictability, potentially stimulating interest through scent-tracking and investigative movement. Finally, the rotation-based deployment plan was designed in accordance with AZA-recognized enrichment protocols, avoiding daily repetition by varying scents and locations and limiting use to two or three sessions per week. This approach not only allowed for a gentler introduction but also mirrored how the system might realistically be integrated into long-term enrichment planning. These intentional variations aimed to sustain engagement while minimizing the risk of habituation over time. The novelty of bubbles can be retained with an essential oil or food extract mixed into a bubble solution and easily swapped into the machine by emptying the solution, rinsing, and refilling it.

4.2 Design Iteration and Zookeeper Involvement

Over five months of development, the system evolved to meet the needs of both bear participants and human users. Zookeepers, Curators, and the Animal Wellbeing Advisor (2nd author) with over 120 years of combined professional experience in the zoo field collaborated throughout the process. They advised on animal safety and behavior, keeper workflows, and expected guest experience. Their sustained commitment through design reviews, idea generation, workshops, and hands-on testing, helped shape scent selection, sensor placement, and timing logic to fit both the habitat layout and the bears' engagement style. This collaboration reflects a multi-species, human-centered approach, applying HCI principles like participatory design and stakeholder alignment to develop animal technology.

Based on the requirement for non-food based intervention and the bears' olfactory capability, we quickly settled on the choice of scent-based interaction. The exact nature of the interaction kept developing over months. Early ideation included a range of interaction concepts: manual bubble release, a button interface, scratch-and-sniff stations, and even visitor-triggered scent dispersal. Concerns around bear safety, destructiveness, toxicity, and the ethics of consent led us to favor passive, bear-initiated activation. Bubble delivery also evolved through iterations, we explored several off-the-shelf machines and compared them in terms of bubble size, density, speed and noise.

The design process unfolded through three key prototype iterations (see Fig. 3), each reflecting evolving insights from bear behavior, stakeholder feedback, and practical deployment considerations: (1) Ideation in tandem with the Zookeepers, involving getting to know the bears as a species and individuals. (2) Post-pilot session modifications involving sensor calibration, further understanding of Zookeeper comfort with technology, and validation of the system concept with the participants. (3) Following study deployment, the system was modified again such that the final version given to the zoo for long-term use was Zookeeper friendly and best fit the prospect of use with multiple species.

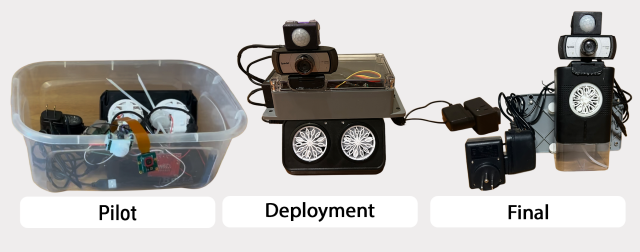


Figure 3: The bubble machine's design underwent several versions. The pilot version was encased in a plastic box to facilitate angle adjustment and positioning. The deployment version had an updated camera and simpler design. The final version given to the zoo used the same camera and sensor pair, with an updated bubble machine to allow for a longer solution duration.

4.3 Components

4.3.1 Hardware. The system consisted of two modified off-the-shelf bubble machines, each with a micro-controller, a passive infrared (PIR) sensor, a relay module, a webcam, and a small fan (see Figure 2 above). PIR sensors were selected because they detect thermal motion, minimizing false triggers from ambient movements (e.g. leaves). Ultrasonic sensors were avoided, as they are more prone to interference from zoo noise and can be perceived by bears [102], potentially causing stress. Components were housed in a waterproof box with reinforced wiring, on/off switch, and plug-and-play setup. During deployment, the units withstood outdoor conditions without failure. A fan was added to direct the bubbles into the habitat. Each unit costs $125 in components, making it significantly less expensive than typical zoo-oriented enrichment devices which often range from several hundred to thousands of dollars [26, 76, 105].

4.3.2 Scented Bubbles. Scent selection was guided by zoo staff recommendations and the bears' enrichment history. We opted not to include an unscented bubble condition based on prior work in the field and because even "unscented" formulations would likely carry detectable cues to the bears' highly sensitive nose. Lemon was included as it is a favorite food for the bears, often used as a reward while training the bears' husbandry behaviors. Maple bacon and peanut butter were included because maple syrup and peanut butter are sometimes spread inside or around enrichment objects in their habitat. Together, these scents tied the intervention to known positive contexts. Bubble solutions were prepared from commercially available, non-toxic products. Edible, pet-safe maple

bacon[2] and peanut butter solutions (*BubbleLick*, Flavored Bubble Treats) were diluted at a 1:3 ratio with an unscented bubble solution (*Bttyu*, Bubble Gun Concentrate) to reduce the intensity. For lemon, a few tablespoons of lemon flavor oil (*Simply Organic*, Lemon Flavor) was mixed directly into the unscented solution. All mixtures were reviewed and approved by zoo staff as safe for animal use (e.g., ok for incidental ingestion during foraging).

4.4 Safety, Welfare, and Ethical Safeguards

The system was designed to prioritize animal welfare, agency, and safety. The devices were intended for installation outside the habitat (either behind gates or above viewing areas) to prevent contact with animals or guests. Bubble outlets were to be aligned with the mesh allowing safe dispersal without disrupting habitat infrastructure. All materials, including non-toxic bubble solution, were pre-approved by zoo staff. The interaction was designed to be low-impact: each bubble release was short (15 seconds), allowing bears to disengage simply by moving away. The built-in cool-down mechanism was designed to reduce risks of overstimulation, pausing activation after five minutes of continuous triggering. These safeguards aimed to respect the animals' autonomy and align with enrichment best practices and ethical deployment.

5 Study Methods

This study investigated the effects of our novel, bubble-based olfactory enrichment on the behavior and welfare of two zoo-housed black bears, as well as its educational and experiential impact on human visitors and zoo staff. The primary goals/research questions were to evaluate whether the enrichment could (1) diversify the bears' activity patterns enhancing locomotion, foraging, and habitat use, (2) provide engaging and non-food-based enrichment opportunities aligned with the zoo's welfare objectives, (3) agency, and (4) promote human stake-holder experience through learning, empathy, connection with nature and system engagement.

The animal-focused component of the study followed a controlled, repeated-measures design across baseline and deployment phases. The baseline phase consisted of four observation sessions, at the same time of day as the deployments would be, without the bubble enrichment (separated into feeding and post-feeding baselines), while the deployment phase spanned seven sessions across three weeks with the enrichment introduced in rotation with the zoo's standard enrichment activities. Parallel to this, data were collected from visitors through short surveys, and from Zookeepers and volunteers through staff surveys. We considered visitors not only as observers but also as stakeholders in this inter-species technological intervention.

5.1 Participants

5.1.1 Animal Participants. This study involved Smoky and Bubba, two male black bears housed at Stone Zoo since they were two years old. The bears were brought to a rescue as cubs when they were only five pounds each and were determined to be unreleasable due to their habituation to humans. The bears displayed some undesirable behaviors such as pacing and inactivity (Figure 4), which the zoo works to reduce through rotating environmental enrichment and increasing complexity of their habitat.



Figure 4: The two black bear participants. Bubba (left) typically exhibited pacing behavior, while Smoky (right) was more often observed sitting or lying for extended periods. These distinct tendencies motivated the zoo's efforts to provide varied enrichment to reduce such behaviors.

Designated as "ambassador animals," the bears and their story play a central role in educating visitors about bear conservation and coexistence with humans in the wild. The habitat's front is lined with a long glass wall from which visitors can view the bears (see Figure 5). The middle of the space is dominated by a series of cascading pools that are filled by a waterfall flowing from the rock wall at the back of the habitat. Within the habitat a number of enrichment devices are normally present, most of which Zookeepers hide food in, varying the devices by day. Among them are spinning drums in which food pellets can be placed, plastic drums in which food can be hidden or smeared (in the case of honey, maple syrup, or peanut butter), and plastic balls in which food can be enclosed. Food can also be scatter fed or placed in or on top of the tree in the center of their habitat to encourage standing and reaching.

The bears regularly receive scent-based enrichment that varies in scent and behavioral goals. Non-food enrichments include artificial or natural scent trails and odors from other animals—such as prey or carnivores—used to encourage behaviors like foraging, roaming, or hunting.

5.1.2 Human Participants. Visitor participants were recruited through an anonymous visitor survey distributed at the bear exhibit; no demographic information was collected. Thirty visitors completed the survey ($n = 30$), with twenty surveyed during BearBubbles sessions and ten at other times to allow for comparison. Three expert zoo staff were also invited to complete an anonymous survey to capture professional perspectives on the enrichment. Demographic information beyond professional role was not collected. Two were animal care staff (Zookeepers and trainers), and one held another role (e.g., volunteer or security).

5.2 Protocol

5.2.1 Enrichment Intervention. The study followed a controlled repeated-measures design across two baselines (Feeding and Post-Feeding) and deployment (BearBubbles) phases to assess the effects of the scented bubble enrichment on bear welfare, engagement, and activity. Figure 6 summarizes the protocol. The baseline phase

[2]To the human authors, maple bacon primarily smelled of maple. However, bear olfactory perception is fundamentally different from human perception and we cannot know for certain how the bears perceived any of the scents.



Figure 5: Black bear habitat, shown from left, center, and right viewing angles. Numbered labels (1–4) indicate the locations where BearBubbles devices were placed across sessions, including positions above the visitor glass and on the ground outside the mesh.

comprised four observation days without bubbles, recorded starting with the bears' breakfast routine between 10:00 and 11:00 a.m. The timing changed based on the bears' feeding schedule, which Zookeepers vary to avoid habituation to a strict routine. Splitting the recordings into Feeding and Post-Feeding portions allowed comparison between food-driven behaviors (given the bears' high food motivation) and activity in the absence of feeding. The BearBubbles deployment phase spanned three weeks and seven sessions, with the scented bubble enrichment rotated alongside the zoo's standard enrichment program including food enrichment as part of their meal routines and object enrichment around the habitat.

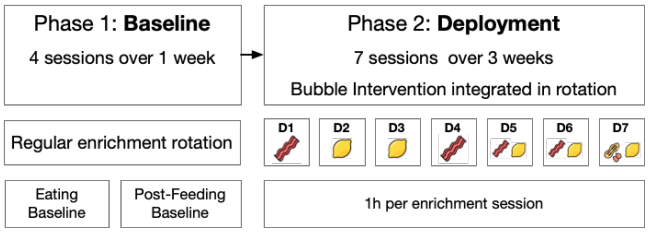


Figure 6: The experiment followed two phases: (1) *Baseline* (four sessions, with feeding and post-feeding segments) and (2) *Deployment* (seven sessions). Each deployment introduced one or more scent (maple bacon, lemon, or peanut butter) for 1h enrichment sessions. Data collection combined behavioral coding, spatial tracking, interaction logs, and visitor and staff surveys.

All BearBubbles sessions occurred in the morning following the bears' usual breakfast routine, ensuring food-based motivation would not compete with the olfactory intervention. Each session lasted approximately one hour, during which the system(s) remained and could be triggered by the bears. Scents changed across days to build familiarity before eventually including multiple scents at once Each session began with a two-minute warm-up of the machines releasing bubbles to cue the bears to their presence. Once activated, the system released a 15-second burst of bubbles when triggered. Continuous release lasted up to five minutes if a bear remained in the detection/trigger zone, followed by a three-minute pause to prevent over-saturation and encourage natural investigative behaviors.

5.2.2 Visitor Survey. To evaluate the educational and experiential impact on human visitors, anonymous voluntary surveys were distributed via QR codes at the exhibit. Based on validated zoo research frameworks (particularly the Thematic Conversation Observation Record for educational outcomes [72, 88] and Luebke's empathy assessment for affective responses [55]), the survey used a five-point "smiley face" Likert scale to ensure accessibility across ages. Items measured visitor experience, empathy toward the animals, educational impact (including conversation topics), and observation of enrichment interactions. Responses were collected during deployment sessions and later as a baseline, allowing comparisons of how enrichment shaped visitor experience.

5.2.3 Staff Survey. A parallel survey was distributed to zoo staff to capture professional insights into animal welfare, enrichment value, operational feasibility, and visitor impact. Staff reported their zoo role before answering questions about observed behaviors, enrichment suitability, integration with zoo operations, and visitor engagement. Five-point Likert-scale questions were paired with open-ended prompts for qualitative observations, enabling staff to identify positive behaviors, stress signals, or suggestions for improvement. Participation was voluntary.

5.3 Ethical Considerations

All procedures were approved by the zoo's IACUC (ZNE ID: 2025-74) and institute IRB (NU IRB: 25-05-07). As animals cannot provide consent, the study followed precautionary protocols. Research staff were trained to recognize signs of distress and to alert zoo personnel if needed. A zoo enrichment team member observed the first three deployment sessions to confirm safe, voluntary engagement. In later sessions, trained zoo volunteers offered visitor education and support. A research team member was present during all sessions to monitor the system and answer questions. Emergency contacts and staff support were on hand throughout. No adverse responses were observed during the study.

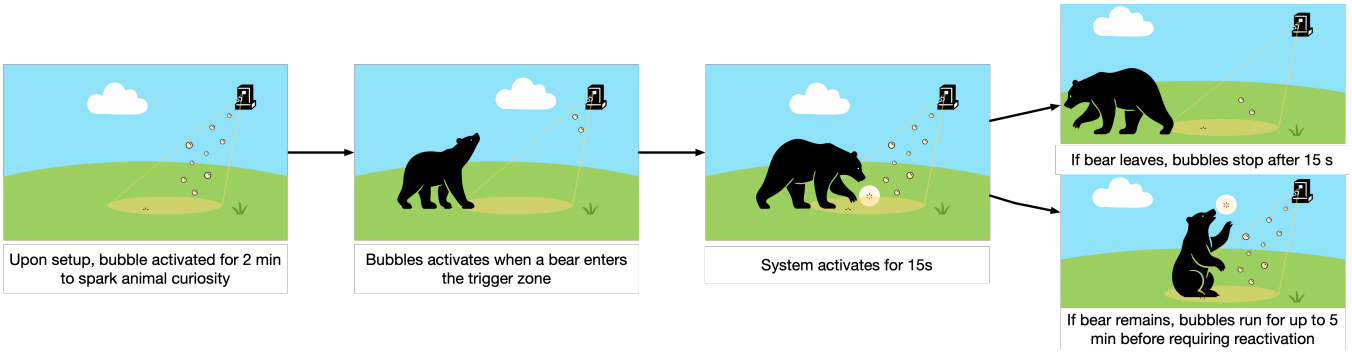


Figure 7: The BearBubbles protocol involved three distinct phases. (1) When the system was initially set-up, it triggered a two-minute bubble release to indicate presence of the bubbles to the bears. (2) The system was activated for 15-second intervals by the bears when they entered the trigger zone. (3) The bubbles stopped releasing either when the bears left the trigger zone or when five minutes of continuous bubble release had occurred.

5.4 Data Collection

The data collected across four baseline and seven deployment sessions include video recordings, detailed and timestamped field notes, and anonymous surveys. Four cameras captured bear activity providing multiple high resolution perspectives.

As the system was designed to provide food-like stimulation without increasing dietary intake, we partitioned baseline sessions into two conditions: Feeding and Post-Feeding. This enabled comparisons between deployment sessions, natural feeding behavior, and activity after their diet was consumed.

In addition to animal data, anonymous surveys were administered to both visitors and zoo staff. The visitor survey assessed educational and experiential impact of the system at the exhibit. The zoo staff surveys were distributed to animal care staff and exhibit volunteers and evaluated perceived welfare value and long-term feasibility.

6 Analysis

In total, we collected 35 hours of video footage, resulting in 1,682 annotated behavioral labels. Analyses focused on understanding how the scented bubble enrichment influenced bear activity, diversity of behavior, and habitat use, as well as how visitors and staff perceived the intervention.

6.1 Ethogram and Coding

Behaviors selected for the ethogram were selected from the zoo's approved enrichment plan for the two black bears. This plan emphasizes species-appropriate behaviors, with the goal of creating opportunities for animals to engage in targeted natural activities such as foraging, locomotion, and exploratory behaviors. From the zoo's extensive list combined with contextual user experience labels, we selected and categorized ten behaviors most relevant to the bubble deployment (see Figure 8 and Table 1). Foraging behaviors were sometimes sparse when coded separately; therefore, analyses used a grouped "Foraging" category to ensure comparability across conditions.



Figure 8: Examples of bear behaviors coded during the study. Illustrated behaviors include resting (*laying, sitting*), foraging-related (*scratching, pawing, sniffing, licking*). These examples provided visual references for ethogram-based coding of video data.

6.1.1 Coding and Reliability. Video footage was annotated using Behavioral Observation Research Interactive Software (BORIS) [30]. One author annotated the entire dataset, and a second author independently coded 20% of the dataset to establish inter-annotator reliability. The annotators achieved a Cohen's Kappa value of $\kappa = .7525$ suggesting substantial agreement [63], and then resolved disagreements by discussion and consensus. Field notes were used to supplement annotations, as portions of the habitat areas were not fully captured or too distant for discernment on video.

6.2 Quantitative Analysis

Behavioral metrics were calculated as both a percentage of session duration and rate (bouts per minute) to account for variation in

Table 1: Ethogram of behaviors coded during the study. Detailed descriptions guided systematic coding, while simplified descriptions provide lay-friendly interpretations.

Category	Behavior	Detailed Description
Resting	Laying	Bear lies in prone position or lateral recumbency, eyes open or closed.
	Sitting	Bear rests with rump on the ground and body upright, remaining immobile.
Locomotion	Walking	Bear moves forward in lateral-sequence gait.
	Pacing	Bear walks repetitively back and forth on a fixed path (2 cycles min, A–B–A).
Foraging	Sniffing	Bear moves nose with purposeful short inhales/exhales toward object or area.
	Licking	Bear extends tongue to make contact with an object.
	Pawing/ Scratching	Bear manipulates substrate with paws or claws, unassociated with locomotion.
	Eating	Bear consumes food by extracting, chewing, and swallowing, including manipulation of food-based enrichment devices.
BearBubbles	System trigger	Bear enters sensor zone and triggers bubble release.
	Anticipation	Bear orients head with ears erect and directed toward machine.

session length. Conditions were defined as Feeding, Post-Feeding, and BearBubbles deployment.

This analysis allowed us to test whether deployment influenced foraging, locomotion, or resting behaviors relative to baselines. In particular, we examined whether scented bubbles increased foraging relative to baseline enrichment (post-feeding) conditions and how walking and resting varied across contexts.

To evaluate habitat use, heatmaps were generated from annotated video footage. Using a semi-manual annotation interface, each bear's position was separately marked at consistent time intervals across all sessions. Heatmaps were then aggregated for Feeding, Post-Feeding and BearBubbles sessions.

6.3 Visitor and Staff Survey Analyses

Survey data were analyzed separately from behavioral video data. Visitor and staff surveys were summarized using descriptive statistics, and open-ended responses were thematically coded. Because responses were brief and relatively few in number, two authors grouped them into themes through iterative discussion and reached consensus from the outset rather than coding independently. Staff feedback was further used to contextualize quantitative and spatial results, particularly regarding animal welfare value, animal agency, and operational feasibility of the enrichment.

6.4 Limitations

The small number of sessions limited statistical power, particularly for differentiating between individual scents. Uneven interaction with scents could be influenced by many factors beyond odor preference. Consequently, scent-level analyses were restricted to descriptive reporting.

7 Results

7.1 Bear Behavior Results

7.1.1 Assumption Checks. Shapiro-Wilk and Levene's tests indicated mixed adherence to normality and homogeneity. For duration data, *Foraging* (SW $p = 0.113$, Levene $p = 0.359$), *Laying* (SW $p = 0.196$, Levene $p = 0.372$), *Sitting* (SW $p = 0.248$, Levene $p = 0.359$), and *Walking* (SW $p = 0.370$, Levene $p = 0.148$) satisfied assumptions for two-way ANOVAs. For behavioral rate data, *Laying* (SW $p = 0.944$, Levene $p = 0.379$) and *Sitting* (SW $p = 0.081$, Levene $p = 0.134$) also met assumptions. By contrast, *Foraging* showed variance homogeneity (Levene $p = 0.148$) but violated normality (SW $p = 0.042$), and *Walking* violated both (SW $p = 0.017$, Levene $p = 0.019$), so Welch ANOVAs were applied in those cases.

7.1.2 Duration (% of session). Duration results are visualized in Figure 9 (top). *Foraging* duration differed significantly by Condition (two-way ANOVA, $p = 0.033$, $\eta^2 p = 0.32$, moderate). Post-hoc contrasts (Welch t-tests, Benjamini-Hochberg corrected across 15 duration comparisons) revealed more foraging during BearBubbles than during Post-Feeding alone ($p = 0.038$, $g = -1.36$, large). No other foraging contrasts reached significance.

Laying duration also varied by Condition (two-way ANOVA, $p = 0.309$, $\eta^2 p = 0.39$, medium-to-large), but no pairwise comparisons survived correction. *Sitting* duration showed no significant differences. Pacing duration data was too sparse for analysis.

Walking duration was strongly affected by Condition (two-way ANOVA, $p < 0.001$, $\eta^2 p = 0.61$, large). Pairwise BH-corrected tests indicated that Feeding elicited more walking than Post-Feeding ($p = 0.041$, $g = 2.10$, very large), suggesting that food strongly drove locomotion.

7.1.3 Behavioral Rate (bouts/minute). Behavioral rate results are visualized in Figure 9 (bottom). *Foraging* rate significantly differed across conditions (Welch ANOVA, $p = 0.003$, $\eta^2 = 0.25$, moderate). Post-hoc contrasts (Welch t-tests, Benjamini-Hochberg corrected across 15 rate comparisons) revealed higher foraging rates during BearBubbles than Post-Feeding Baselines ($p = 0.002$, $g = -1.35$, large), suggesting that scented bubble enrichment partially increased foraging relative to contexts lacking any eating behaviors.

Laying rate did not differ overall, but a Bear × Condition interaction was significant ($p = 0.020$), indicating individual differences in resting patterns. Pairwise contrasts were non-significant.

Sitting rate showed a marginal effect of Condition (two-way ANOVA, $p = 0.044$), though post-hoc tests were non-significant and effect sizes small. *Pacing* rate had insufficient data for analysis.

Walking rates differed sharply by Condition (Welch ANOVA, $p < 0.001$, $\eta^2 = .70$, very large). Post-hoc tests showed higher rates with Feeding than Post-Feeding ($p = 0.001$, $g = 2.58$, very large), Feeding than BearBubbles ($p = 0.006$, $g = 2.51$, very large), and BearBubbles than Post-Feeding alone ($p = 0.008$, $g = -1.22$, large). These results suggest that scented bubble enrichment increased or broke up walking relative to post-feeding, though not to the level seen when food was present.

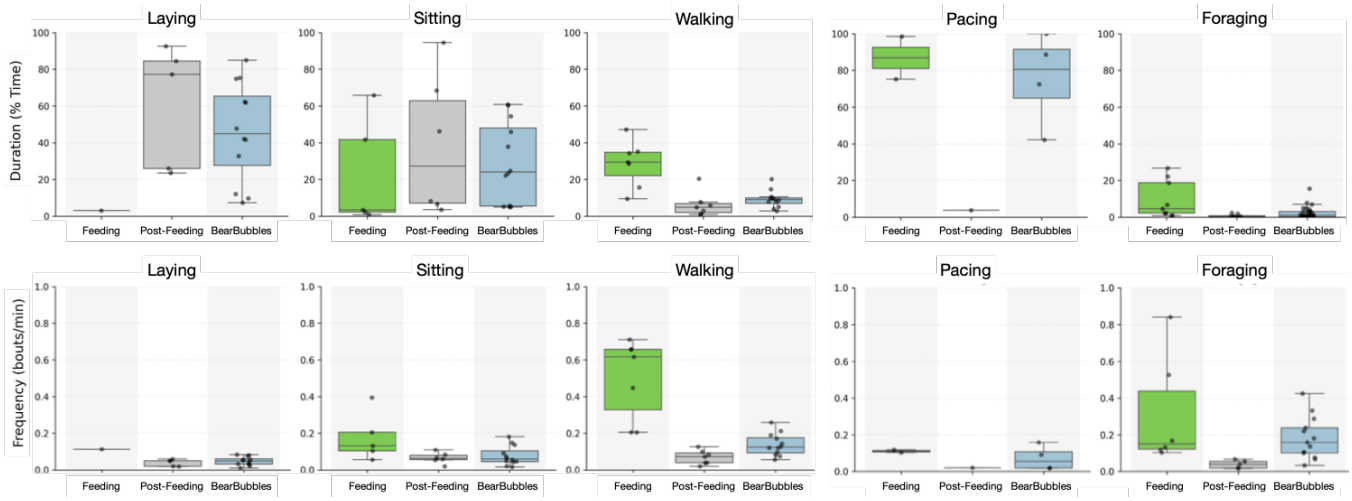


Figure 9: Behavioral duration (top; % of session time) and behavioral rate (bottom; bouts/minute) across Feeding, Post-Feeding, and BearBubbles conditions. *Foraging* occupied a greater proportion of time and occurred at higher rates during BearBubbles than during Post-Feeding baselines, while *Walking* was most prominent during Feeding and remained elevated during BearBubbles relative to Post-Feeding.

7.1.4 Heatmaps. Figure 10 shows heatmaps for both Bubba (top), while and Smoky (bottom). In the Post-Feeding baselines, Bubba's characteristic behavior is visible, particularly in Sessions 1 and 2 near the visitor glass. When food was present, Bubba moved more widely across the habitat, reflecting strong food motivation. During BearBubbles deployment, there was still pacing observed, but it was broken up by walking and other behaviors as well. Feeding baselines consistently elicited greater movement, but Smoky generally remained sedentary, sitting or lying in one to two preferred locations across sessions. Across the BearBubbles deployment this was less so the case with an increase in walking relative to Post-Feeding baselines in between sedentary behaviors.

7.1.5 Observed Usership. In addition to the quantitative analyses reported above, we extracted qualitative evidence of direct bear-bubble interaction from our coded video data and accompanying field notes. These narrative observations illustrate how the animals engaged with the enrichment in practice, capturing moments that speak to the bears' experience of the system. Clips identified during BORIS coding, together with field notes, provide concrete examples of how the scented bubbles were investigated and incorporated into ongoing behavior (see supplementary video for visual reference). Table 2 summarizes the instances of direct bubble interaction by bear, scent, and behavior. Across the seven deployment sessions, the BearBubbles systems were triggered 198 times, with 44 of those events accompanied by clear anticipatory behaviors from the triggering bear. Although no clear pattern emerged, the ratio of apparently anticipated triggers peaked on Session 3.

7.2 Visitor Survey Results

7.2.1 Quantitative. We first examined whether visitors who reported seeing the bears interact with bubbles ($n = 14$) differed from those who did not ($n = 6$). Because no variables met normality assumptions, Mann–Whitney U tests with Benjamini–Hochberg correction were used across seven items; no differences emerged (all adjusted $p > 0.05$; $|r| < 0.30$). Conversation-topic distributions also did not differ ($\chi^2 = 4.97$, $p = 0.76$). These groups were therefore combined into a single BearBubbles sample.

Table 2: Observed direct interactions with scented bubbles by bear, scent, and behavior. Values show total instances coded from video and field notes, with per-session averages in parentheses.

Bear	Scent	Sniff	Lick	Paw	Track	Total
Bubba	Bacon	4 (1)	2 (0.5)	2 (0.5)	4 (1)	8 (2)
	Lemon	7 (1.4)	4 (0.8)	1 (0.2)	1 (0.2)	12 (2.4)
	Peanut	1 (1)	2 (2)	–	2 (2)	3 (3)
Smoky	Bacon	8 (2)	4 (1)	11 (2.8)	2 (0.5)	23 (5.75)
	Lemon	12 (2.4)	13 (2.6)	–	1 (0.2)	25 (5)
	Peanut	–	–	–	1 (1)	–

We then compared this combined BearBubbles group ($n = 20$) with baseline visitors surveyed outside such periods($n = 10$). Across seven survey items (see Figure 11), no significant differences were detected after correction across the seven items (all adjusted $p > 0.05$; $|r| < 0.37$). Given these consistent null findings, we report only overall patterns: across all visitors, ratings on experience, educational value, empathy-related items, and nature connection were uniformly high, and visitors who saw the BearBubbles enrichment typically felt that bubbles enhanced their visit.

Check-all-that-apply responses about conversation topics likewise revealed no differences between ($\chi^2 = 2.35$, $df = 8$, $p = 0.97$). Conversations were dominated by discussions about the two bears (identities, behaviors, and lived experience) and general bear facts (Figure 12).

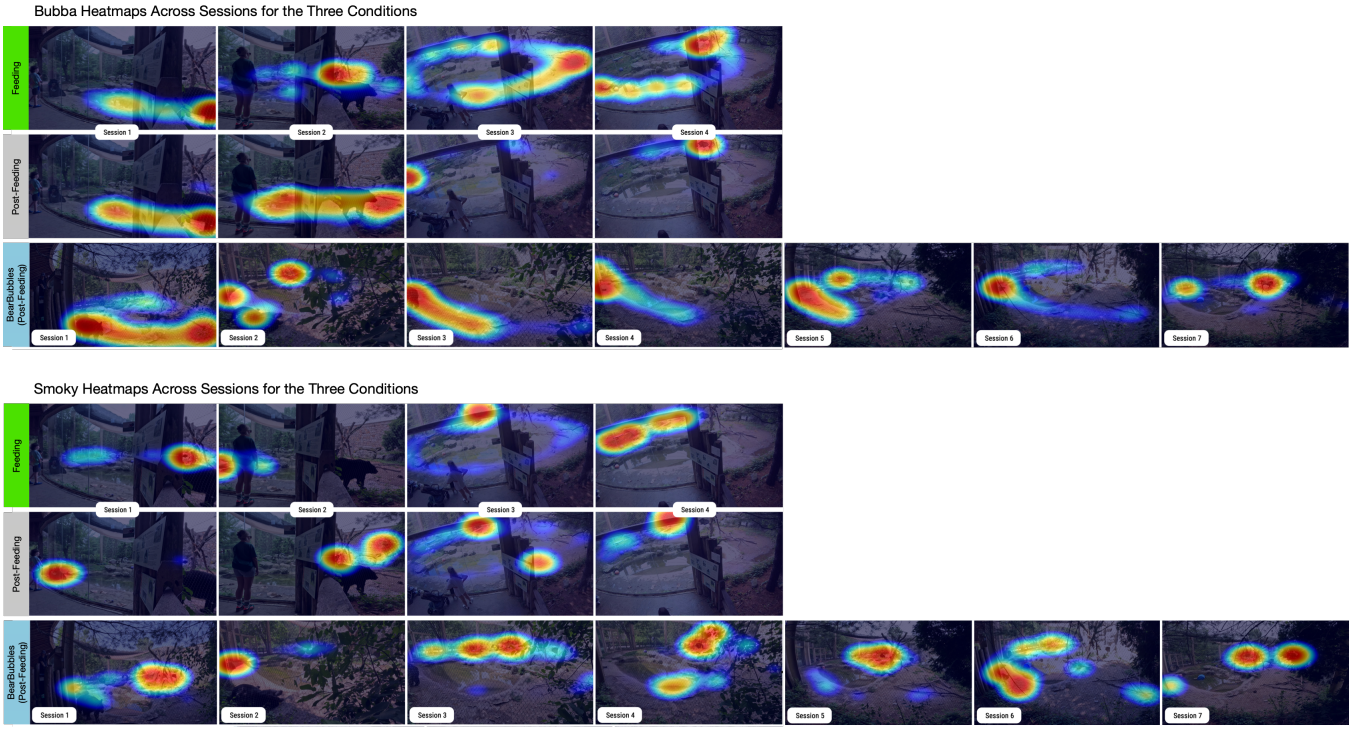


Figure 10: Locomotion heatmaps for Bubba (top) and Smoky (bottom) across all sessions. The top row shows Feeding baselines, middle row shows Post-Feeding baselines, and bottom two rows show scented bubbles (BearBubbles) sessions after feeding. For both bears, the BearBubbles sessions restored movement relative to Post-Feeding baselines.

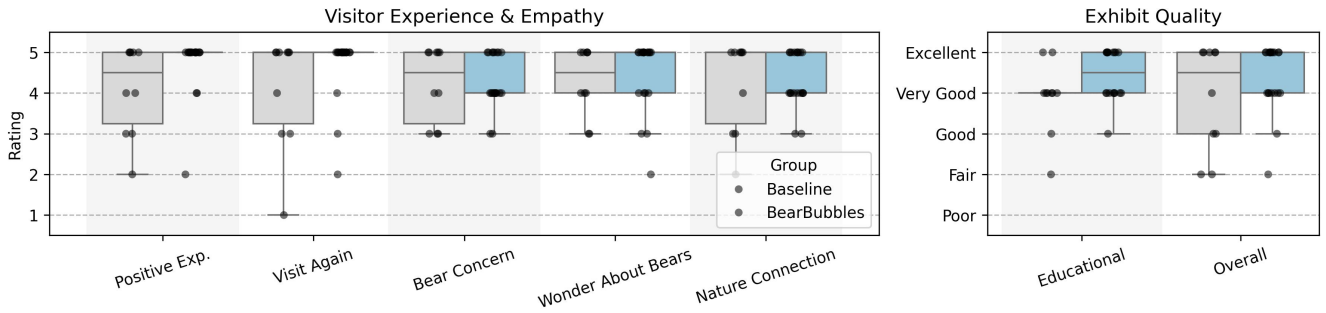


Figure 11: Visitor survey ratings during BearBubbles sessions (where baseline is gray and BearBubbles is blue) and outside of such sessions (Baseline). Items assessed visitor experience and empathy (left) and exhibit quality (right). Ratings were consistently high across both conditions, with no significant differences after correction.

7.2.2 Qualitative Feedback. We summarize open-ended comments from visitors during BearBubbles sessions and those surveyed at other times.

Visitors with BearBubbles (11 of 20). Two themes emerged: (1) engagement and (2) empathy for the bears. *Engagement (8 of 20).* Participants described the enrichment as engaging for both the bears and people. Scented bubbles "animate[d]" (P6) or "intrigued the bears" (P7), though one visitor noted possible mild annoyance (P10). Several appreciated seeing a new enrichment for the bears (P13, P16). Visitors also described social engagement: bubbles drew attention from afar (P20), prompted conversation (P11), and excited children while intriguing the bears (P7, P12). *Empathy (3 of 20).* A smaller raised welfare concerns, including perceptions that the bears seemed sad (P2), the enclosure small (P19), or the bubbles slightly bothersome (P10).

Six participants reported learning new information (e.g., a bear's lifespan, how to distinguish between the two bears, and the enrichment goals).

Visitors without BearBubbles (7 of 10). Comments centered on exhibit significance and empathy. *Exhibit Significance (2 of 10).*

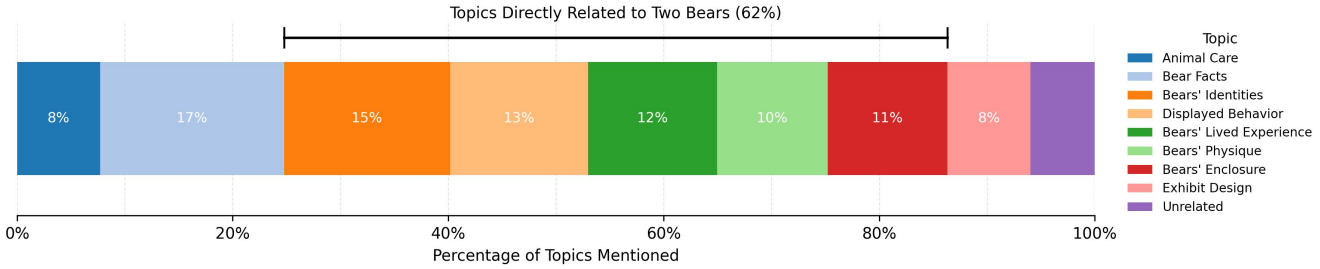


Figure 12: Distribution of conversation topics mentioned by participant visitors across baseline and BearBubbles, showing no significant differences between groups. Overall, 62% of discussions directly referenced the two bears.

Two the exhibit as a highlight of their visit (P22, P25). *Empathy (2 of 10).* Visitors noted bear behavior patterns (P25) and concerns about the habitat size (P28).

Half reported learning something new (e.g., bears' solitary or crepuscular habits, longevity, long-term residence at the zoo). One participant reported no new learning.

7.3 Zoo Staff Survey Results

Three zoo staff members completed the survey: two Animal Care Staff (ACS) and one Other Zoo Staff (OZS). We report results separately where relevant. Across all staff, none observed any signs of stress or negative reactions from the bears, and all agreed that the system supported positive behavioral responses.

7.3.1 Animal Care Staff ($n = 2$). On a 5-point scale from *Not at all enriching (1)* to *Highly enriching (5)*, care staff rated the system as moderately enriching ($M = 3.0$, $SD = 0.0$). They reported slightly greater behavioral diversity during deployment compared to typical days ($M = 3.5$, $SD = 0.71$), with one staff member noting that the bears "showed interest some of the time." Suggested improvements included "clear and specific timing in the future" (ACS1) and "more staff involvement from the start" (ACS2).

Regarding visitor experience, ACS1 observed that "most visitors seemed to either ignore the presence of the research or were interested and engaged with it," with visitors spending somewhat more time at the exhibit during BearBubbles sessions. ACS2 highlighted that "guests did enjoy when the bubbles blew into the public area. With staff there, there was more interaction with guests, which enhances and extends the visit," though noted no change in total time spent.

7.3.2 Other Zoo Staff ($n = 1$). The other staff member rated the system as highly enriching (5 out of 5) and described positive behaviors such as "more walking around and playing." They suggested that "varying the scent more would add diversity and keep it exciting." This staff member also rated behavioral diversity as higher than typical days (4 out of 5) and noticed that visitors spent "somewhat more" time at the exhibit when BearBubbles was active.

7.3.3 Overall Staff Responses. Across all staff, the system was viewed as integrating reasonably well with zoo operations ($M = 3.33$, $SD = 1.15$ on a 5-point scale, where 5 meant *Very well integrated*). All three staff members affirmed that the collaboration provided learning opportunities, that they would welcome similar research collaborations in the future, and that they could see the system being used long term as part of the enrichment rotation. The overall impact of the research project on the zoo environment was rated positively ($M = 4.0$, $SD = 0.0$).

System design feedback included requests for improved weatherproofing and durability, larger reservoirs for bubble solution and multiple placement options, and easier setup through stands or tripods.

8 Discussion

This study evaluated BearBubbles, a proximity-triggered, olfactory-first enrichment system for two zoo-housed black bears. We return here to the four research questions presented in the introduction: (Q1) whether the system provided positive enrichment; (Q2) what bear usership looked like; (Q3) whether the bears exhibited any sense-making of agency to control the system; and (Q4) how human stakeholders perceived the intervention.

8.1 Interpretation of Results: Enrichment Outcomes

RQ1 asked whether BearBubbles provided positive enrichment measured in terms of behavior, habitat utilization, sustainability, and activation. Across these dimensions, we observed patterns suggesting that the system successfully extended species-typical behaviors and supported greater activity compared to post-feeding baselines.

8.1.1 Foraging. As expected, feeding baselines produced the highest levels of foraging (10.9% of coded time on average), dropping to 1.0% post-feeding. During BearBubbles sessions, foraging rose to 5.3% on average, showing the system extended investigatory behavior without additional food provision, which was the primary enrichment goal. Beyond large-scale locomotion or overt pawing, bears frequently reacted to bubble release with subtle snout, lip, and nose movements indicative of olfactory investigation (0.19 bouts per min on average during deployments vs. 0.04 bpm post-feeding). The persistence of these multi-scale behaviors across sessions is notable because food-based enrichment often ends its impact once discovered and consumed. By contrast, BearBubbles encouraged an extended duration of investigative behaviors that did not terminate upon locating the scent source, maintaining sensory impact

over time without Zookeeper replenishment, offering a potential sustainable form of enrichment.

8.1.2 Locomotion. Locomotion patterns also shifted across conditions. Feeding baselines showed high levels of walking as bears searched for scattered diet items, while post-feeding baselines were characterized by reduced movement and greater pacing. Deployments increased walking bouts per minute from 0.07 on average in post-feeding baselines to 0.14, closer to the 0.50 observed during feeding. Walking was often interspersed with investigative pauses, suggesting greater diversity of movement sequences. Pacing was distinguished from walking during behavioral labeling based on path repetition and postures differentiated by body contact with the ground. These findings indicate that BearBubbles not only increased locomotion but also diversified the structure of locomotor behavior.

8.1.3 Habitat utilization. Visual observations showed that in post-feeding baselines, activity clustered within less than ~20% of the surface of the habitat, while deployments appeared to extend use to nearly half. Both bears approached bubble release zones regularly, and increased movement was often concentrated near enrichment locations, without noted avoidance. Such expansion is a meaningful welfare outcome: encouraging animals to engage with their full environment is a recognized indicator of enrichment success.

Together, these observations suggest that BearBubbles promoted multiple enrichment outcomes: extension of foraging beyond food, increased walking, and expanded space use. While the project's scale limits generalization, the consistency of these effects across sessions suggests the system provided multifaceted enrichment for the bears. This aligns with prior work showing that olfactory enrichment can stimulate exploratory activity [17, 96]. By coupling scent release with animal-triggered activation, BearBubbles provided repeated, varied opportunities for engagement, meeting its design goals of promoting natural and sustained behavior. The Zookeepers have also expressed strong interest in adapting the BearBubbles system to other olfactory dependent species with strong destructive tendencies such as pigs, otters, and large felids, for whom the interactive but external nature of the device would be appealing. However, each case would need its own behavioral grounding and safety review.

Finding highlight (Q1). BearBubbles enriched daily activity by extending foraging behaviors, diversifying locomotion, and broadening habitat use, demonstrating the potential of interactive olfactory systems for bears in managed care.

8.2 Bear Usership

RQ2 asked what bear usership looked like with BearBubbles. Across all seven deployments, both bears engaged with the system, including direct bubble interaction. At least one instance of direct engagement occurred at each session, including pawing at clumps of bubbles, sniffing and licking residues, and scratching the ground where bubbles had landed and dissipated. These behaviors show that both bears incorporated the system into their daily activity. Additionally, **the lingering investigations, highlight the potential of scented bubbles to extend enrichment impact even after visual cues were gone.**

Notably, interactions differed based on bubble form-factor. When bubbles were airborne, the bears primarily tracked them visually or with nose movements. **More active responses occurred once bubbles landed on the floor, on their fur, or accumulated into heavier clusters.** Dense, persistent bubble clusters elicited the most consistent investigation, suggesting the physical form of grounded or tactile encounters prompted more active behaviors than transient airborne stimuli.

Overall, BearBubbles provided opportunities for multi-modal interaction. Besides direct pawing or licking, bears engaged olfactorily and visually with the bubbles, while the motors' auditory cues added an additional sensory layer. In line with frameworks that define animal usership as requiring sensory feedback, beneficiary framing, and empirical testing [47], our results show that the system successfully provided feedback across multiple senses, was oriented toward animal welfare goals, and was evaluated through systematic observation.

Finding highlight (Q2). BearBubbles supported sustained engagement across sessions. Direct interactions occurred in every session, with the most active behaviors arising when bubbles settled on the floor or fur. While scent preferences could not be determined, the system created flexible opportunities for bears to interact on their own terms.

8.3 Agency and Sense-Making

RQ3 asked whether the bears exhibited some sense-making of their agency over the system. Across seven deployment sessions, both animals activated BearBubbles repeatedly. Daily positive engagement behaviors associated with foraging, indicated meaningful interaction with the system beyond mechanical activation. Anticipatory behaviors were regularly observed immediately before release, including slowed pace when approaching the machine, pausing in the trigger zone, or orienting ears and gaze toward the device. These behaviors suggest the bears may have recognized spatial contingencies between their presence and bubble release.

However, it is not possible to determine whether the animals understood the causal relationship between their actions and the system's activation. Anticipatory behaviors could reflect expectation of outcomes without cognitive modeling of control. **Nevertheless, by requiring presence in the trigger zone, the system ensured activation and their environment was always under the bears' control.**

This combination of trigger agency and partial evidence of anticipation is significant. Animal welfare guidelines highlight that enrichment should provide opportunities for choice and control [4, 85], and frameworks of animal usership emphasize sensory feedback, beneficiary framing, and empirical testing [47]. BearBubbles fulfilled these criteria, while also raising questions about how different levels of sense-making can support meaningful agency. **In this sense, the system illustrates how HCI methodologies for evaluating user experience can be extended into multi-species**

contexts, where agency emerges from design affordances without requiring explicit causal reasoning.

Finding highlight (Q3). Bears exhibited anticipatory behaviors suggesting partial sense-making of bubble release, while the system design ensured that activations were always animal-initiated. This illustrates how agency can be supported through interaction design even when cognitive understanding remains uncertain.

8.4 Human Stakeholder Perspectives

RQ4 asked how human stakeholders such as Zookeepers and visitors perceived the new enrichment system. Visitor surveys revealed no significant differences between those who did and did not see BearBubbles, nor between baseline and BearBubbles sessions. This null result is informative: despite concerns that an artificial enrichment might reduce empathy or connection to nature, ratings of concern for wild bears, reflection on the bears' lived experience, and nature connection remained consistently high. The system did not diminish conservation-oriented attitudes or perceived exhibit quality.

Open-ended feedback also highlighted distinctive engagement during BearBubbles sessions. Visitor comments indicated shared engagement across humans and animals. Comments also continued to reflect empathy and welfare awareness, suggesting that the playful enrichment did not overshadow reflection on the animals' well-being. Visitor perspectives are essential to zoo functioning, providing guidelines for zoo policies and practices. Zoos' central mission is to educate their visitors and survey results confirmed that the system did not interfere with those objectives.

Zoo staff also responded positively. Expert animal care staff rated the enrichment as effective, observing somewhat greater behavioral diversity and acknowledging visitor interest, while another staff member rated it as highly enriching and noted more walking and play. Across all staff, the system was seen as producing no stress behaviors and integrating reasonably well into daily routines. Feedback emphasized the need for refinements to support long-term use—such as improved weatherproofing, larger reservoirs, and more flexible placement options, pointing to the practical considerations that shape adoption in real-world zoo settings.

Finding highlight (Q4). BearBubbles appears to maintained and even extended visitors' empathy while fostering moments of joint engagement. Staff viewed it as a feasible and beneficial enrichment with clear avenues for improvement.

8.5 Relation to Zoo Olfactory Enrichment

Our findings resonate with and extend previous zoo-based olfactory enrichment research. Prior work found scents stimulate investigatory and foraging behaviors but are limited by short-lived responses and habituation [17, 96]. Our participants engaged repeatedly across three weeks, increasing foraging and locomotion versus post-feeding baselines. While sample size limits long-term claims, the continuation of these behaviors across sessions suggests that the **ephemeral yet renewable nature of airborne bubbles** may help sustain engagement beyond static scent applications.

A further extension lies in the **mode of delivery**. Most prior zoo studies have relied on scent applied to substrates such as logs, cloths, or bedding [8, 27, 66] while BearBubbles created dynamic stimuli that were smelled, seen, and felt on fur. Engagement was especially noticeable when bubbles remained long enough to prompt repeated investigation. This demonstrates how delivery format can shape behavioral outcomes, creating multi-modal olfactory enrichment.

Finally, our results suggest ways that scent enrichment can support **agency and variety.** Because BearBubbles was proximity-triggered, activation always depended on the animals' movement, embedding choice into the enrichment. The use of two devices allowed **simultaneous exposure to different scents,** opening doors for comparative engagement that most single-scent approaches do not support. While our study was not designed to test preferences, the framework highlights how interactive delivery systems could enable nuanced studies of animal olfactory preferences.

8.6 Design Considerations

Our study highlights several design considerations for developing interactive olfactory systems in zoo contexts and for extending bubble-based interaction beyond human-centered deployments.

Iterative piloting with staff. Close collaboration with animal care staff was critical in refining placement, timing, and safety protocols. Piloting the system ensured animal engagement and Zookeeper feasibility, underscoring the importance of participatory design for sustainable enrichment.

Scent formulation and customization. Bears showed greater interest in synthetic food-related scents than the lemon flavor oil, raising questions about how animals perceive odor quality and "naturalness." Future investigations could benefit from designing and rotating "scent recipes" that balance stability with species-specific ecological relevance.

Environmental robustness and delivery format. Outdoor deployment introduced variability uncommon in lab-based HCI work. Wind sometimes dispersed bubbles rapidly, which led to little response, and at other times produced effective clusters and sustained interaction. Designing for robustness under such conditions is crucial for translating HCI prototypes into animal-facing systems.

These considerations inform future zoo enrichment design and extend insights to the CHI community's work on olfactory and bubble-based interfaces. Prior research such as *SensaBubble* [83], *UTAKATA* [42], and *BubblEat* [62] emphasized the ephemeral, multisensory qualities of bubbles in controlled human contexts. *BearBubbles* shows how these qualities manifest differently in outdoor, animal-centered environments, where delivery format, scent formulation, and environmental forces play central roles.

8.7 Contribution to HCI

This study contributes to ongoing discussions about how HCI can extend beyond human-centered frameworks to include more-than-human perspectives and the research builds on prior CHI work

exploring non-food, sensory-driven, and agency-oriented enrichment across species, including auditory enrichment in zoo contexts [50], interactive systems supporting animal connection [51], and investigations of ergonomics and interaction design for animal-operated interfaces [48]. Echoing recent work that frames animal–technology interactions as entangled relationships rather than isolated events [2, 3, 47], our findings highlight key intersections between HCI and ACI.

- **Human-in-the-Loop:** Zoo enrichment illustrates that humans remain part of the interaction ecology. Keepers oversaw deployment, and visitors co-shaped the interpretive context. Designing for zoo animals thus requires recognizing humans as engaged participants, echoing with prior ACI work on co-presence and mediation [57].
- **Multi-species Interconnectedness:** The system demonstrates how technological experiences and perception can in multi-species context, supporting HCI's broader turn toward multi-species ecological perspectives [82, 95] beyond single user–interface dyads.
- **Methodological Innovation:** By combining ethological methods with HCI notions of user-ship and engagement, we provide a framework for evaluating technology in multi-stakeholder, ecological settings. This connects to broader HCI conversations around methodological pluralism in field settings [23].
- **Designing for Otherness:** Finally, this work underscores the value of embracing animal otherness. Designing with otherness challenges HCI to move beyond anthropocentric interaction models and engage with animals as users in their own right [36, 57].

By situating zoo-based research within HCI contexts, this work points toward an expanded vision of interaction where animals are recognized as users in their own right, and where human responsibility, empathy, and creativity shape futures of more-than-human computing.

9 Conclusion

This paper presented BearBubbles, a proximity-activated olfactory enrichment system designed for two geriatric black bears. By integrating behavior-based welfare goals with HCI/ACI methodologies, the system demonstrated how interactive olfactory enrichment can promote natural foraging and locomotion behaviors while preserving animal agency and not adding additional food items. Across three weeks of deployment, the enrichment increased behavioral diversity, fostered multi-modal engagement, and received positive feedback from both visitors and zoo staff.

As an early exploration, our work has several limitations. (1) The study was limited to two individuals over three weeks, constraining generalizability. Some behaviors, such as pacing, were too sparse for analysis, and scent-specific effects could only be described qualitatively. (2) Anticipatory behaviors suggested sense-making but cannot confirm internal control models; agency therefore remains inferred, not demonstrated. (3) PIR sensors occasionally mistriggered due to light or bird activity, while wind and enclosure mesh altered bubble dispersal.

This approach provides several benefits. (1) **Non-food enrichment.** The system encouraged foraging and locomotion without weight gain risks. (2) **Agency through spatial choice.** Proximity sensing ensured bear-initiated rather than imposed enrichment. (3) **Zookeeper-friendly and cost-effective.** Units cost ~$125, were plug-and-play, and remained robust outdoors. (4) **Adaptability across species.** The core design principles of BearBubbles (olfactory-forward interaction, distance-based actuation, and low-intrusion deployment) generalize to many other scent-oriented, physically strong species. Zoo staff expressed interest in trials with suids (which are highly scent-motivated but destructive) and felids such as pumas (using readily available catnip-scented bubbles). (5) **Methodological contribution.** The study combined ethogram coding, spatial analysis, anticipatory behavior tracking, and stakeholder surveys, providing a holistic framework for enrichment evaluation.

Looking forward, we provide the zoo and any researchers with resources to reproduce the final system for continued enrichment, alongside simple ratios for customizing bubble scents to species-specific contexts. Given that many large mammals share similar welfare goals, BearBubbles offers a strong, scalable foundation for future olfactory enrichment systems that extend beyond bears to benefit other species.

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