Audio Augmentation of Manual Interactions to Support Mindfulness

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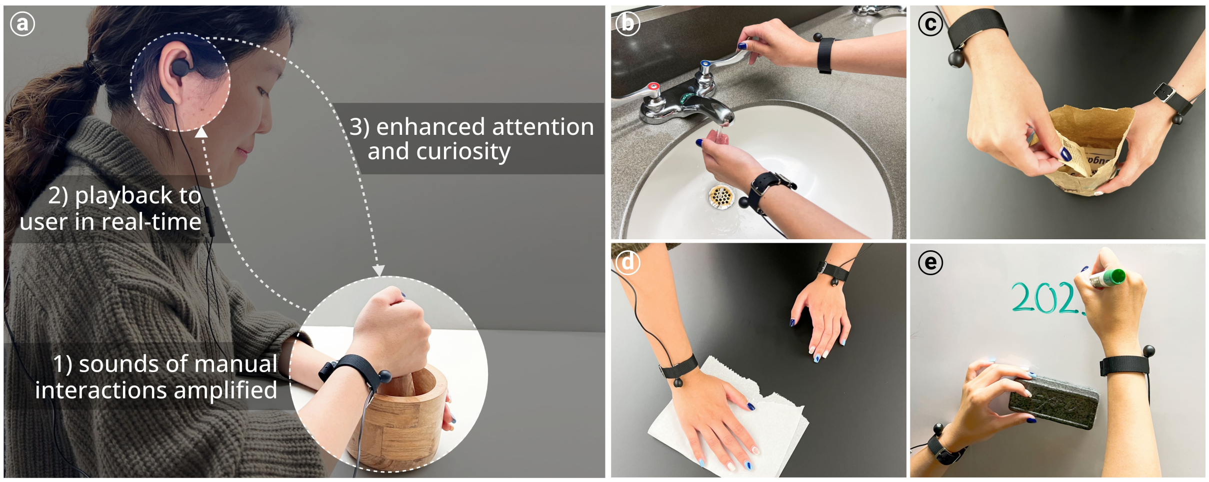

Fig. 1. (a) We propose a wearable device that amplifies sounds produced by ongoing hand interactions and plays them back to the user in real time, encouraging attention and curiosity toward the present-moment experience. The device supports mindfulness during everyday activities, such as (b) washing hands, (c) retrieving items from a paper bag, (d) cleaning a table, and (e) writing on a whiteboard. The figure is a posed demonstration of device use, with consent from the depicted individual.

Mindfulness is the state of maintaining attention to the present moment with curiosity and openness. Existing mobile technologies to support mindfulness focus on formal practices such as meditation, requiring dedicated space and time. However, everyday mindfulness—a more flexible form of practice woven into routine activities such as washing hands or cooking—remains under-supported. To address this gap, we introduce a wearable device that adopts a sensory-driven approach to foster two key components of mindfulness, attention and curiosity, in everyday contexts. Our device amplifies sounds produced by the user's hand interactions to make them more salient, such as the sounds of hands rubbing together or

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fingertips sliding across surfaces. By playing back the amplified sounds to the user in real time, the device leads to a fresh perspective on mundane interactions. We conducted a preregistered in-lab study with 60 participants to evaluate the device in an everyday task: object exploration. We found that audio augmentation enhanced self-reported state mindfulness, directing user attention to auditory properties of objects that would otherwise be overlooked. Behaviorally, audio augmentation caused participants to interact with objects for a longer duration than participants who did not experience audio augmentation. We also found that participants exhibited more trial-and-error exploratory behavior patterns with audio augmentation than without, suggesting increased curiosity.

CCS Concepts: • **Human-centered computing → Empirical studies in ubiquitous and mobile computing**.

Additional Key Words and Phrases: Sensory Augmentation, Mindfulness

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1 INTRODUCTION

The human mind often wanders, drifting to thoughts about the past or future that are unrelated to the present moment [23, 62, 92]. For example, you might be cooking while thinking about a recent awkward conversation, or spending time with friends while your mind drifts to unfinished work. This tendency to unintentionally disengage from the present-moment experience has been shown to decrease self-reported happiness [62, 103] and impair cognitive performance [79, 93]. In contrast, *mindfulness* offers a different mode of engagement, which involves (1) the self-regulation of attention to maintain focus on the present moment, and (2) an attitudinal orientation toward that experience characterized by curiosity, openness, and acceptance [15, 82].

Mindfulness can be practiced both formally and informally [14]. Formal practices require dedicated time and space [14, 69], such as meditation, QiGong, and yoga [30, 105]. Informally, mindfulness practices can be interwoven into routine activities [69, 104, 121], paying deliberate attention while engaging in activities such as washing hands, cleaning the table, or writing, as shown in Figure 1 (b - e). Informal practices of mindfulness are also commonly referred to as everyday mindfulness [110].

With the rise of mobile technology, we have seen increasing support for formal mindfulness practices [25, 31, 33, 83, 91, 98]. Mobile applications such as *Calm* [1] and *Headspace* [2] offer guided instruction from experts, making meditation accessible in digital, portable formats. Physiological sensing, such as breathing [43], heart-rate [96], or brain activity tracking [29], enabled by mobile technology, further allows users to monitor their states during formal practice. Despite the promise, everyday mindfulness, a more flexible and dynamic form of practice woven into everyday activities [42], remains largely under-supported. While previous research has recognized that technology could help support everyday mindfulness [69] and proposed speculative designs [71], it has rarely progressed beyond conceptual ideas.

In this work, we propose to support everyday mindfulness through a sensory-driven approach. We introduce a wearable device that amplifies sounds around the user's hand and plays them back to the users in real time. With physical manipulation with our hands central to daily interactions, the device heightens the user's auditory experience of their ongoing actions. It engages with two key components of mindfulness: attention and curiosity. Audio augmentation makes the sounds of present-moment actions—such as hands rubbing together or the crinkling of papers—more salient [48], thereby lowering the barrier for users to self-regulate their attention to these cues. Additionally, audio augmentation modulates the sensory outcomes of manual interactions, introducing a fresh perspective on routine interactions. The sensory outcomes, being slightly different from expectations, thus serve as a touchpoint for users to maintain curiosity in everyday interactions [52].

As the first step to understanding how the proposed device influences mindfulness, we conducted a preregistered in-lab study with 60 participants. Participants were asked to engage in an everyday task, object exploration, while wearing the device. Our findings revealed that participants who experienced audio augmentation of manual interactions (*device group*) reported a higher state mindfulness compared to those who did not (*control group*). Behavioral coding also demonstrated that our device affected two key mechanisms of mindfulness: attention and curiosity toward the present moment. Participants in the *device group* were more likely to notice auditory properties of objects they interacted with that would otherwise be overlooked by the *control group*. Behaviorally, participants spent more time exploring the objects with audio augmentation than without. *Device group* were also more likely to exhibit trial-and-error patterns in their explorations behaviorally than the *control group*, indicating heightened curiosity. Lastly, we discuss insights from the study and considerations when leveraging audio augmentation of manual interactions to support mindfulness.

2 RELATED WORK

2.1 Mindfulness and Practices of Mindfulness

In modern psychology, mindfulness describes the state of openly attending, with awareness, to one's present-moment experience [15, 28]. In this work, we build upon the definition proposed by Bishop et al. [15], who operationalized mindfulness through two key components: (1) self-regulation of attention toward the present moment, and (2) an attitude of curiosity, openness, and acceptance toward that experience.

Mindfulness can be practiced both formally and informally [41, 110]. Formal practices involve dedicated, structured exercises—such as sitting/walking meditation [80], yoga [38], and Tai Chi [20]. These formal practices usually require individuals to set aside time and temporarily withdraw from ongoing activities to train in a controlled manner [14, 69]. In contrast, informal mindfulness practices involve weaving mindfulness into routine activities [69, 104, 121], which could be as simple as mindfully washing dishes [42] or folding clothes [41]. Thus, informal mindfulness practices are also referred to as *everyday mindfulness* [110].

Both formal and informal practices of mindfulness have strong clinical importance [28, 45]. One well-established example is Mindfulness-Based Stress Reduction (MBSR) [55, 56], a manualized treatment program that combines mindfulness meditation, yoga, and body awareness techniques. It has been widely used to reduce chronic pain [57, 58], emotional distress associated with medical illness [95, 106] and enhance general well-being [9, 117]. Moreover, mindfulness-based approaches have been applied in the treatment of a wide range of syndromes, such as substance abuse [17], Attention-Deficit/Hyperactivity Disorder (ADHD) [19] and eating disorders [66].

2.2 Mobile Technology to Support Formal Practices of Mindfulness

Building on the well-documented benefits of mindfulness, the rise of mobile technology has made traditional, formal mindfulness practices more portable and accessible to wider audiences. Commercial mobile applications such as *Headspace* [2] and *Calm* [1] adapt verbal instructions from expert coaches into digital formats, allowing users to engage in meditation anywhere they choose. More recently, live-streamed sessions have also become increasingly common, with users around the world to join the same meditation or yoga class at the same time[51, 70]. With the rise of immersive technology, formal mindfulness practices have also been adapted into virtual reality experiences, such as with a virtual avatar as the instructor to guide users through meditations [33].

In addition to content delivery, mobile technology also affords physiological sensing capabilities. For instance, Hao et al. [43] developed a smartwatch system that tracks respiration rate during meditation. Other biosignals, such as heart rate [72, 96] and electroencephalography (EEG) brain activity [25, 26, 29, 65], have also been used to infer users' states during mindfulness practices. These signals are often mapped to additional cues rendered by the device to help users maintain focus during formal mindfulness exercises. For instance, Roo et al. explored mapping breathing and heart rate to dynamic projected imagery on a sandbox, enabling users to become more aware of their bodily states during meditation [96]. These attention-guiding cues are not limited to visual feedback [65, 74, 91], but can also be auditory [24, 29, 91] or even tactile feedback [29, 32]. Ahmed et.al, studied how different modalities affect guidance toward mindfulness in meditation [49]. Beyond sitting meditation, PULSE introduced a user interface that supports mindful motion through slow, continuous, and gentle touch interactions on a mobile phone screen [21]. RunMe [109] offers adaptive soundscapes responsive to physiological changes of the user to support running meditations.

2.3 Technology to Support Everyday Mindfulness

While mobile technology has made significant progress in supporting mindfulness, most existing interfaces are tailored for formal practices [31, 89]. In these contexts, users typically set aside dedicated time and space to engage in mindfulness practice and follow the interface's guidance to focus on specific cues—such as through verbal instructions [1, 2] or biofeedback-driven signals [29, 91].

However, informal mindfulness contexts—where practices are integrated into everyday activities—remain largely unsupported by mobile technology [71]. Informal practices can be more accessible to novices [42], but they can also be more challenging, as sustaining deliberate attention in dynamic, everyday settings is difficult—especially for those who already find formal practices demanding [86]. Li et al. found that even experienced practitioners with long-term routines often struggled to maintain daily practice [69]. They highlighted design opportunities for technology to emphasize short-term benefits as a way to spark users' interest and foster deeper engagement with mindfulness [69].

Only recently have we seen efforts to adapt elements of formal mindfulness guidance to be more accessible in in situ contexts. For example, Choi et al. [22] and Gemicioglu et al. [39] designed subtle tactile cues to implicitly guide breathing during routine activities. Tan et al. [108] took this a step further by exploring an "on-the-go" style of guided instructions to make mindfulness practices more accessible during casual walking with augmented reality glasses. We extend this line of exploration by moving beyond instruction-based interfaces commonly used in formal mindfulness practices, and instead adopting a sensory-driven approach to support key building blocks of mindfulness in everyday contexts.

3 A SENSORY-DRIVEN APPROACH TO SUPPORT EVERYDAY MINDFULNESS

In this work, we adopt a sensory-driven approach to support everyday mindfulness, engaging with both the self-regulation of attention and curiosity orientation of mindfulness, as operationalized by Bishop et al. [15].

3.1 Audio Augmentation to Support Attention

In formal mindfulness practices, mobile technology often guides users by telling them what to focus on. For instance, such interfaces might instruct users to *"close your eyes and observe your breath"* or *"notice the sounds around you-near and far."* This approach leverages a top-down strategy [37, 60, 97], guiding attention by setting goals and giving instructions. While effective in controlled settings, a top-down strategy alone may fall short in everyday mindfulness. In these cases, external prompts can introduce additional cognitive demands—especially when users are already navigating a multitude of sensory signals interwoven with their ongoing interactions. As a result, users may find it difficult to anchor their attention and maintain a mindful state, leading to inconsistency and uncertainty in their practice [69, 86].

Thus, in the context of everyday mindfulness, rather than instructing users to be more attentive, we explore a sensory-driven (bottom-up) approach [37, 60, 97] to lower the barrier to self-regulation of attention. We do so by making sensory cues related to present-moment actions more salient, so it's easier for users to anchor their attention to them. Since manual interactions are central to many daily activities, we designed our system to enhance the salience of hand-generated sounds—such as fingers brushing against clothing, tapping on surfaces or crinkling paper. We modulated the salience of these sounds by amplifying their loudness, which is a primary driver of auditory salience [48]. While other features of sound—such as pitch, frequency, or reverberation—can also influence salience [48, 61], we chose to modulate only loudness to preserve the perceptual qualities of the original sounds. This design choice aims to avoid making the sounds of manual interactions feel artificial or disconnected from real-world experiences, which could hinder rather than support mindfulness. We also prioritize auditory augmentation (rather than visual or tactile modalities) because it can be achieved without requiring bulky hardware like headsets or motorized components, making it well-suited for everyday contexts.

3.2 Audio Augmentation to Spark Curiosity

To support an orientation of curiosity, existing mobile technology supporting formal mindfulness practices prompts users with questions like: *"Does each inhale and exhale feel the same, or is there variation?"*. These questions introduce intellectual uncertainties, encouraging users to stay curious about their sensory experience. However, much like the case for guiding attention, this approach can become less effective in everyday contexts, where surroundings are overly familiar. In such environments, users habituate to what they are used to [111, 112], making it more difficult to sustain curiosity and engage mindfully with routine experiences.

Similarly, we adopted a sensory-driven approach by introducing a fresh perspective on everyday, mundane interactions. Through audio augmentation, our device modulates the sensory outcomes generated by manual actions. From an active (Bayesian) inference standpoint [34, 35], perception and action are guided by the brain's attempts to minimize prediction error—the mismatch between expected and actual sensory input. For example, when we touch a table, we anticipate a certain level of sound based on prior experience. By amplifying these auditory outcomes in real time, our device introduces a form of Bayesian surprise [52]—a deviation from predicted sensory input. This surprise, in turn, drives curiosity and motivates epistemic behaviors aimed at minimizing the uncertainty [36]. Again, the decision to only introduce amplification to familiar sensory cues reflects our goal for the device to act as a temporary scaffold for mindfulness—not to replace it. When users stop using the device, they are still able to notice and relate to the same sounds that were previously amplified. Over time, this may help users develop the ability to attend to the present moment without relying on external aid, a possibility we return to later in the paper.

4 SYSTEM IMPLEMENTATION

To implement our sensory-driven approach to supporting mindfulness, we designed our device to preserve the natural characteristics of sound and maintain low latency. Below, we outline the key components of our system.

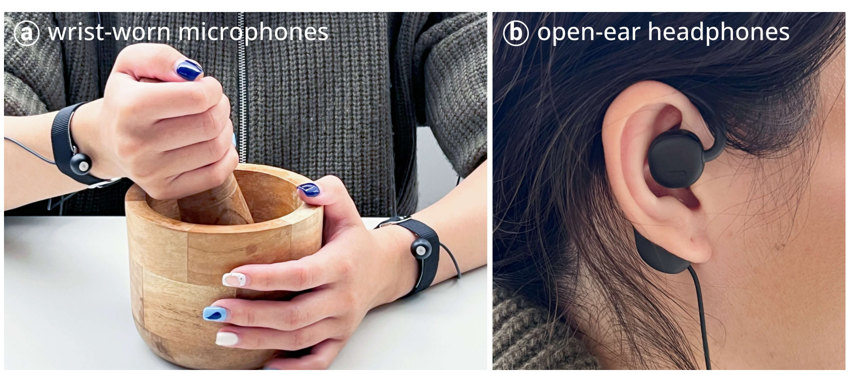

Fig. 2. Overview of the system. (a) The system captures sounds produced by everyday manual interactions through wrist-worn microphones. (b) These sounds are digitally amplified and played back to the user through open-ear headphones.

4.1 Input and Output Devices

Figure 2 shows our system's hardware setup. We used *Sonic Presence SP 15C* microphones [7] to capture sounds around the user's hands, which serve as the input devices. The microphones are attached to the user's wrists using wrist-worn bands. Two microphones were included in the device to approximate how human ears perceive sounds spatially. By placing one microphone on each hand, the device preserves the stereo characteristics of human hearing. The input audio is then processed through our software pipeline (described later) and played back through a pair of headphones [6]. The selected headphones also support stereo output, with the left-hand microphone outputting to the left earphone, and the right-hand microphone outputting to the right earphone. We specifically chose to use open-ear headphones that sit outside the ear canal, allowing users to stay aware of their physical surroundings while experiencing augmented sound layered over ambient noise. To minimize latency, both input and output devices are wired to a host laptop.

4.2 Audio Augmentation

Our device achieves audio augmentation of manual interactions through a combination of two methods: (1) the physical placement of the microphone on the wrist and (2) digital gain applied to the audio stream.

Placing a microphone on each wrist amplifies sounds near the user's hand by reducing the distance to the target sound source. Normally, sounds near the hand are heard at a distance of about 78 centimeters, considering the average single arm length [53]. By positioning the microphone on the wrist, the distance is reduced to approximately 19 centimeters, for the average hand length [99]. The exact distance depends on the user's arm/hand size and types of interaction. Theoretically, the amplification achieved by placing the microphone on the wrist can be modeled using the Inverse Square Law for sound [76]. In this context, d_1 denotes the distance between the hand and the audio source, while d_2 denotes the distance between the ear and the audio source. $L(d_1)$ and $L(d_2)$ denote the sound pressure levels at these respective distances: $L(d_2) = L(d_1) + 20\log_{10}\left(\frac{d_1}{d_2}\right)$. Note that this model accounts only for distance-based sound attenuation and does not incorporate the effects of room acoustics, which may further reduce sound levels as it propagates.

In practice, most amplification achieved by our device is done by applying a digital gain. Our system enhances sound by processing the input stream from the wrist-worn microphones and adjusting its gain before playing it back to users. We used JUCE [4] for the backend of our system, which is a widely used framework for audio applications. Canonically, a 10 dB increase is perceived as twice as loud [102]. Thus, for $\Delta L = L(d_1) - L(d_2)$, the perceived change in loudness is approximated to $2^{\frac{\Delta L}{10}}$ of the original perceived loudness.

To determine the level of audio augmentation for supporting everyday mindfulness, we conducted a formative study with two experienced mindfulness coaches. Both participants have practiced mindfulness for more than 20 years, are certified in Mindfulness-Based Stress Reduction (MBSR), and regularly lead mindfulness training in educational and corporate settings. In the study, participants first get familiar with the experiences delivered by our device. They were then asked to identify the audio augmentation level that *felt most natural and helpful for everyday mindfulness*. We provided a web-based interface with a slider that allowed them to adjust the device's audio augmentation level while interacting with everyday objects. Both experts selected a digital gain of 15 dB, which was subsequently implemented in the final prototype. Augmentation levels below this threshold were perceived as insufficient, while higher levels were considered too jarring.

4.3 Latency Measurement

As the system is designed to enhance the user's auditory experience in real-time, minimal latency is a critical requirement. Significant mismatches between visual and auditory cues can result in a disorienting user experience [10, 107]. Thus, we examined the latency introduced by the system.

To measure system latency, we played a ringtone from a distance of 10 centimeters to the system's microphone. The output was recorded using two methods: (1) capturing the sound played back through the open-ear headphones after it had passed through the entire end-to-end processing pipeline, and (2) recording the same ringtone using a separate microphone placed near the audio source, serving as a baseline for comparison. The latency was measured by averaging across 30 trials.

We found that the latency introduced by our end-to-end system is 21.3 ms (SD = 1.02). This value falls below the just noticeable difference (JND) threshold for audio latency in musical applications, which is typically 30 ms and above [67, 75, 100]. While some studies have measured optimal minimal perceivable thresholds as low as 10 ms [116], these thresholds are often determined in highly controlled experimental settings. Such conditions do not necessarily reflect human performance in real-world situations, where attention is divided among multiple tasks and users need to navigate a multitude of sensory signals.

5 EXAMINING IMPACT OF AUDIO AUGMENTATION OF MANUAL INTERACTIONS

As the first step to examine how audio augmentation of manual interactions affects state mindfulness, we conducted a preregistered in-lab study with 60 participants. In the study, participants engaged in everyday interactions—specifically, object exploration—while wearing the device.

Fig. 3. (a) Posed demonstration of the study setup. A volunteer performs object exploration tasks while two table-mounted cameras and one front-facing camera capture hand and body movements. The depicted individual provided consent for the use of this image in the manuscript. (b) Four familiar objects used in the study: storage bag, pen & paper, scissors, and coffee cup. (c) Four unfamiliar objects used in the study: a two-dimensional handbag, a human-face-shaped broom and dustpan set, a door-handled mug, and a clamp-like tape dispenser.

5.1 Hypothesis and Research Questions

We preregistered through Open Science Foundation [1] and outlined the key hypotheses as follows.

Our primary hypothesis **H1** focuses on state mindfulness. We hypothesized that participants would report a stronger state mindfulness when interacting with objects with audio augmentation compared to without it. Behaviorally, we tracked users' movements during the object exploration tasks, as exploratory behavior reflects curiosity—one of the core components of mindfulness. Thus, in **H2**, we hypothesized that participants would exhibit more exploratory behavior when interacting with objects with audio augmentation compared to those without it. Finally, given that our device offers a fresh perspective on everyday objects, we also explored the auxiliary benefits of mindfulness. In **H3**, we hypothesized that participants would report a greater sense of awe when interacting with objects with audio augmentation, compared to without.

[1] https://osf.io/9erp4

We formulated a set of research questions to investigate the broader impact of audio augmentation of manual interactions. Specifically, we asked: (RQ1) How does audio augmentation affect users' sense of agency? (RQ2) How does it influence affective states? and (RQ3) How does it shape users' sense of connectedness to the objects? In addition, we explored (RQ4) how audio augmentation affects what participants notice about the objects, as reflected in the questionnaire. Through a post-intervention task, we also examined (RQ5) how prior experience with audio augmentation affects participants' experiences during a subsequent meditation exercise.

As everyday interactions involve both familiar and unfamiliar objects, we also consider how object familiarity impacts the effect of audio augmentation: (RQ6) How does the familiarity of objects interact with the effect of audio augmentation of manual interactions?

5.2 Condition Design

We adopted a mixed-factorial design, with one between-group factor and one within-group factor.

Between-group factor: audio augmentation. To examine the effect of audio augmentation introduced by our device, we divided participants into two groups. In the *device group*, participants interacted with the objects while the device actively amplified the sounds occurring around their hands. In the *control group*, participants wore the same device, but the device remained off and provided no additional auditory cues.

Within-group factor: object familiarity. Everyday mindfulness involves cultivating attention and curiosity toward routine activities. Although daily activities are filled with familiar objects, such familiarity is not inherent—it develops through repeated exposure. For example, a new tool may become familiar over time with regular use. To investigate how the device functions across the spectrum of familiar and unfamiliar objects in everyday interactions, we included object familiarity as a within-group factor. This design allows us to examine how object familiarity may interact with the effect of audio augmentation.

Counterbalancing and randomization. Participants were randomly assigned to the *device group* or the *control group*. We counterbalanced the session order for interacting with familiar and unfamiliar objects to minimize order effect. Additionally, we randomized the order in which objects were presented within each session, ensuring that each object was introduced one at a time in a different sequence for each participant.

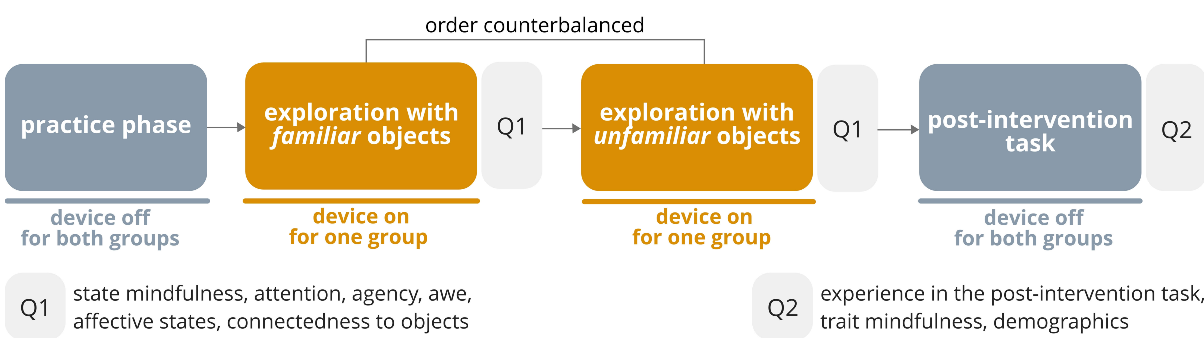

Fig. 4. Overview of study procedure.

5.3 Task Design

The participants' primary task in the study was to explore a set of provided objects, one at a time. One session involved four familiar objects and the other session involved four unfamiliar objects.

Researchers chose the objects drawing inspiration from existing databases on everyday and novel objects [46, 47]. Familiar objects were selected from common household items, while unfamiliar objects were sourced from vendors that specialize in creative or artistic products—items that participants were less likely to encounter in everyday contexts. All selected objects were hand-held in size to ensure ease of manipulation. Through pilot testing, we also made sure that each object produced noticeable sounds audible to the naked ear during typical hand interactions (e.g., grasping, hand manipulation). As shown in Figure 3, the familiar objects included a pair of scissors, a storage bag, a paper cup, and a marker-and-paper set. The unfamiliar objects were a clamp-like tape dispenser, a door-handled mug, a two-dimensional handbag, and a human-face-shaped broom and dustpan set.

In the study, participants were informed that their task was to explore the given objects and there was no right or wrong way to engage with the objects. They were encouraged to interact with them according to their natural instincts. There was no time limit; participants could decide how long to spend with each object. The task was intended to approximate everyday, routine interactions in-lab. Moreover, it was designed to be open-ended without a set goal, allowing for natural variation in attention and interaction style. Such design makes it a suitable starting point for examining the effects of audio augmentation on everyday experiences. Details of the study instructions can be found in supplemental materials.

5.4 Measures

After each object exploration session, participants completed a questionnaire assessing their state mindfulness, attention, agency, awe, and affective states experienced during the session. In addition to these self-report measures, we recorded participants' exploratory behaviors and administered a post-intervention task. The key measures are outlined below, and full details of the questionnaire are in the supplemental materials.

5.4.1 State Mindfulness. To measure the short-term expression of mindfulness (i.e., state mindfulness) during object explorations, we used the 5-item *Mindful Attention Awareness Scale (MAAS) - State* [18], following prior work [108, 109]. Two key mechanisms of mindfulness that our device aimed to support—attention and curiosity—were also measured individually.

5.4.2 Attention. Our device aims to lower the barrier for the self-regulation of attention by modulating the salience of sounds produced by manual interactions. Accordingly, the extent to which the auditory properties of objects stood out to participants is an important indicator for evaluating how effectively the device supports attentional engagement. As an indirect measure of attention, we asked participants to *"describe what you noticed about the [object name]"* in a post-session questionnaire. This question was intentionally designed to be open-ended, avoiding prompts that might bias participants toward particular features or encourage them to generate an exhaustive list of all observed characteristics.

In the post-analysis, we recorded the frequency of sound-related terms mentioned in participants' responses to examine how the device influenced attentional engagement with the auditory properties of objects produced by manual interactions. As an exploratory measure, we also analyzed the sentiment of sentences containing sound-related terms to better understand participants' subjective experience of hearing the heightened sounds compared to the control condition. We focused specifically on sentences that included sound-related terms, rather than analyzing all responses, to avoid confounding effects from comments on unrelated object features (e.g., color or shape) that were not directly influenced by the device's manipulation.

5.4.3 Curiosity. Curiosity is manifested by exploratory behavior [11, 13]. Thus, we video-recorded participants' interactions with objects using three RGB-A cameras, with sounds captured by microphones on the wrist. With this behavior data, we measured both participants' duration of interactions with objects and their exploratory patterns. Interaction duration was calculated as the time between the participant's initial contact with the object and the moment they placed it back on a designated marker, signaling the end of exploration. This measure follows prior work, which used interaction length as an indication for epistemic curiosity [73].

As an exploratory measure, we also analyzed patterns of exploratory behavior, with a particular focus on actions that reflected "trial-and-error" strategies [13]—repeated attempts with variations aimed at discovering or understanding object properties. This measure originates from developmental psychology to evaluate exploratory learning in infants [40, 87, 88] and is an indicator of curiosity-driven exploration in the broader contexts [12, 13].

5.4.4 Agency. Our device employs a sensory-driven approach to support mindfulness by modifying the user's auditory experience during manual interactions. Given this design, it is important to understand whether such audio augmentation affects the users' sense of agency. Preserving agency is essential for technologies aiming at fostering intentional, self-directed attention and awareness. To assess perceived agency, we used an adapted version of *Sense of Agency Scale (SoA)* [114]. Specifically, we selected two items from each of the SoA subscales: positive agency (e.g., *"I am completely responsible for everything that results from my actions."*) and negative agency (e.g., *"The outcomes from my actions generally surprise me."*)

5.4.5 Auxiliary Benefits of State Mindfulness. We also measured auxiliary qualities that correlate with a mindful state—including changes in affective states [44], a sense of awe [118], and connectedness with the physical surroundings [84]. Affective states were assessed using the *Self-Assessment Manikin (SAM) [16]*, which captures three dimensions: valence, arousal, and dominance. Awe was measured using an adapted version of the *Awe Experience Scale (AWE-S)* [119]. We selected one item from each of the following subscales: altered time perception, self-diminishment, vastness, and connectedness. Connectedness with the physical environment was evaluated using an adapted version of the *Inclusion of Other in the Self Scale* [8], a well-established tool for measuring social closeness. The word "other" was replaced with "object" to reflect participants' sense of connection to each object they interacted with during the study.

5.4.6 Post-intervention Measure. Beyond assessing participants' states during audio augmentation, we also examined how prior exposure to audio augmentation influenced participants' subsequent attempt to maintain a mindful state by themselves. Specifically, we adopted a meditation exercise as the post-intervention task. The meditation followed standard object meditation practices [3, 5], beginning with two minutes of guided audio instructions and followed by three minutes of self-directed practice. Participants used a common meditation aid—mantra beads—throughout the session. The device was turned off for all participants during this session. After the session, participants completed a questionnaire to reflect on their experience. We used these qualitative reflections to explore users' ability to self-sustain mindfulness following exposure to audio augmentation. Further details about the meditation script are provided in the supplemental materials.

5.4.7 Individual Differences. To account for individual differences in mindfulness disposition, we administered the Mindful Attention Awareness Scale – Trait (MAAS), which consists of 15 statements reflecting everyday experiences related to present-moment awareness. In addition, we collected demographic information, including age, gender, and ethnicity.

5.5 Procedure

Upon arriving at the lab, participants completed a consent form. Then, the experimenter helped participants put on the device. The study was introduced as investigating how auditory cues affect physical interactions.

The study began with a practice phase to familiarize participants with the object exploration task. Participants explored four test objects (details in the supplemental materials) one at a time, following the same procedure used in the subsequent trial. A labeled marker on the table indicated where each object would be placed. The experimenter placed an object on the marker, signaling the participant to begin exploration. Once the participants finished exploring the object, they returned it to the same marker. The experimenter then replaced it with a new object. During this phase, the device remained turned off for all participants.

The main task session began after the practice phase. In the *device group*, participants began to hear sounds around their hand amplified by the device starting in the main trial. The amplification level was fixed at 15 dB for these participants, as described in Sec. 4. The *control group* wore the same device but did not receive any sound from it. Participants completed two object exploration sessions—one with familiar objects and one with unfamiliar objects. After each session, they completed a questionnaire.

After completing both object exploration sessions, participants took part in the post-intervention meditation task. They were informed that the device would remain off during this exercise, regardless of whether they had found it to be active in the earlier sessions. Following the meditation, participants completed a final questionnaire.

The study took approximately 60 minutes and was approved by Stanford Institutional Review Board (IRB # 71992). Each participant was compensated $25 for their time.

5.6 Participants

Following preregistration, we conducted a power analysis in G*Power. We aimed for a statistical power of 0.9 to detect a small-to-medium effect size (f = 0.2, equivalent to Cohen's d = 0.4) with a standard alpha level of 0.05. The analysis indicated that a total sample size of 64 participants would be required. We recruited 65 participants who were over 18 years old and reported no hearing deficits. One participant's data was excluded due to technical issues, resulting in 64 participants (32 per group) for initial analysis. Specifically, 36 self-identified as females, 26 self-identified as males, and 2 self-identified as non-binary. The average age of participants was 25.1 years old (SD = 4.2). 21 participants identified as Caucasian, 6 identified as African American, 6 identified as Native American, 39 identified as Asian, 9 chose "other". The total added to more than the sample size as participants could select more than one ethnicity.

There was no significant difference in trait mindfulness between the *device group* (M = 4.07, SD = 0.64) and the *control group* (M = 4.25, SD = 0.66) on a 1 to 6 scale, as determined by a one-way ANOVA (p = 0.29).

5.7 Overview of Analysis

Outlier removal. We first performed an outlier analysis on the amount of time participants spent in the object exploration task. Since the task did not enforce time constraints, this step excluded participants with extremely short or long interaction times to ensure that the subsequent analyses reflected typical interaction behavior. Outliers were identified using a modified interquartile range (IQR) rule [115], excluding participants whose interaction times fell more than two IQRs below the first quartile or above the third quartile. This procedure yielded a final sample size of 60 participants for the subsequent analysis: 29 participants in the *control group* and 31 participnats in the *device group*.

Manipulation checks. Participants reported greater familiarity with the objects categorized as *familiar* (M = 4.42, SD = 0.59) compared to those categorized *unfamiliar* (M = 1.74, SD = 0.67) on a 1 to 5 scale (p = 0), confirming the effectiveness of the object familiarity manipulation.

Reliability test. We assessed reliability using Cronbach's alpha for constructs with more than two items. The agency construct showed low reliability (r_α = 0.55), falling below the commonly accepted threshold of 0.6 [113]. To investigate further, we looked into the two subscales: positive agency (r_α = 0.64), which met the threshold, and negative agency (r_α = 0.49), which did not. Due to this inconsistency, we chose to analyze agency at the item level rather than as a composite score. Other multi-item constructs—state mindfulness (r_α = 0.67) and awe (r_α = 0.69)—were above the threshold and were analyzed as composite scores. Affective states (valence, arousal, and dominance) were analyzed separately, as the SAM scale treats them as distinct dimensions.

Analysis model. For all self-report rating measures, we used a linear mixed effect model for analysis. We factored in *audio augmentation*, *object familiarity*, the interaction between audio augmentation and object familiarity, and session order as fixed effects. We modeled the participant identifier as the random effect factor to account for individual differences. The model details can be found in the supplemental materials.

6 FINDINGS

6.1 State Mindfulness

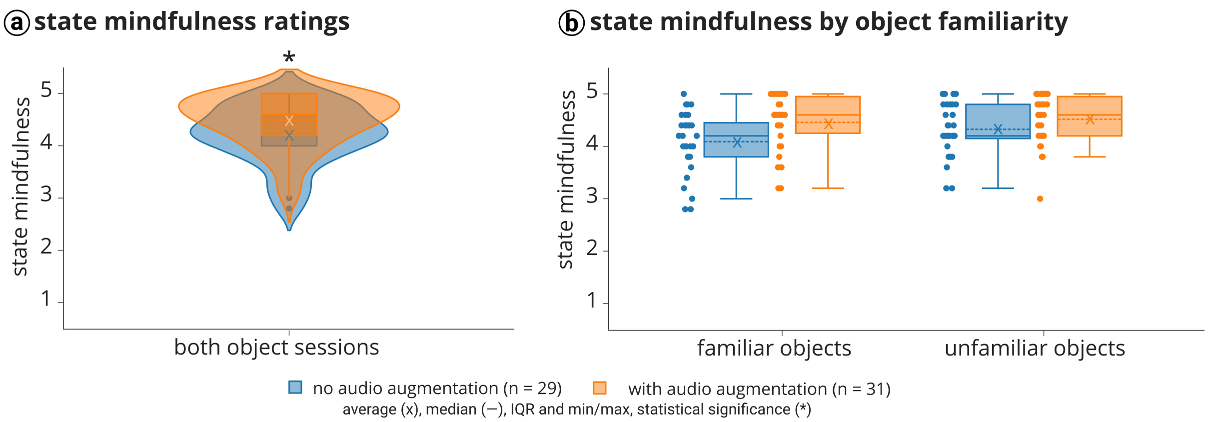

Fig. 5. Results for state mindfulness ratings. (a) State mindfulness across both object sessions. (b) State mindfulness ratings for familiar and unfamiliar object sessions.

Figure 5 shows the distribution of self-reported state mindfulness of each group. A main effect was found for audio augmentation ($F(1,58) = 5.68, p = 0.02$). Participants reported a higher state mindfulness when interacting with objects with audio augmentation ($M = 4.49, SD = 0.49$) than participants without audio augmentation ($M = 4.21, SD = 0.56$). This confirms H1. A main effect was also found for object familiarity ($F(1,57) = 4.73, p = 0.034$). Participants reported a lower state mindfulness when interacting with familiar objects ($M = 4.28, SD = 0.58$) than with unfamiliar objects ($M = 4.42, SD = 0.49$). However, no significant interactions were observed ($F(1,57) = 1.55, p = 0.219$).

Beyond the self-report rating of state mindfulness, we also analyzed how our device affects key building blocks of mindfulness: attention and curiosity to the present-moment experience.

6.2 Attention

6.2.1 Attention to Auditory Properties of Objects. Participants' attentiveness during the task session was assessed through a post-task questionnaire that asked them to describe what they noticed about each object they explored. Since our device was designed to modulate the salience of sounds produced during manual interaction, we specifically focused on participants' attentiveness to the auditory properties of the objects. To quantify this, we calculated the frequency of sound-related terms (e.g., *"sound(s)," "audio," "auditory," "noise(s)," "loud"*) used in their descriptions.

Table 1. Total number of times the words "sound(s)", "noise(s)", "loud", "auditory", and "audio" were used in object descriptions.

Word count of sound-related terms in descriptions of objects

	control group	device group
familiar objects	6	56
unfamiliar objects	6	36
total	12	92

As shown in Table 1, *control group* participants mentioned sound-related terms a total of 12 times (6 for familiar objects and 6 for unfamiliar objects) in the descriptions of all the objects they interacted with. In comparison, *device group* participants mentioned sound-related terms for a total of 92 times (56 for familiar objects and 36 for unfamiliar objects). A linear mixed effect model revealed a significant main effect of audio augmentation ($F(1, 58) = 9.51, p = 0.003$). A main effect was also found in object familiarity ($F(1, 57) = 4.15, p = 0.046$). Participants mentioned sound-related terms more in familiar objects than in unfamiliar objects. A significant interaction ($F(1, 57) = 4.36, p = 0.04$) was also observed between audio augmentation and object familiarity. [2] Pairwise comparisons with Bonferroni correction were then conducted. We found that when interacting with familiar objects, participants in the device group were more likely to notice auditory properties compared to those in the control group ($p = 0.002$). A similar trend was also observed during interactions with unfamiliar objects, although this result was only marginally statistically significant ($p = 0.05$).

These findings suggest that our device effectively draws attention to auditory information that would otherwise be overlooked. Participants in the *control group* were less likely to attend to auditory aspects of the objects compared to those in the *device group*. Looking at the number of participants that referenced these sound-related terms, 9 out of 29 (31.0%) participants contributed in the *control group*, while 19 out of 31 (61.3%) participants did so in the *device group*. A Z-test was conducted and revealed a significant difference ($p = 0.019$).

6.2.2 Sentiment Toward Auditory Properties of Objects. As an exploratory measure, we also analyzed how participants described the sounds they noticed. We extracted all sentences that include the sound-related terms mentioned above, resulting in 82 sentences from *device group* and 12 sentences from the *control group*. Then, we conducted sentiment analysis on these sentences using the NLTK VADER sentiment analyzer [50], with the sentiment output ranging from -1 (maximum negative valence) to 1 (maximum positive valence). Figure 6 shows the distribution of sentiment ratings for sentences with sound-related terms. Due to the imbalance in sample sizes between the two groups, we opted not to conduct statistical tests and instead reported summary statistics.

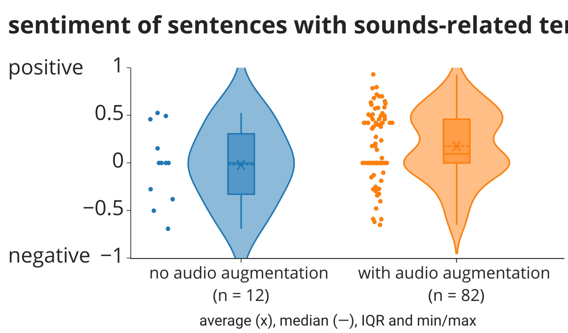

Fig. 6. Sentiment scores of sentences that involved sound-related terms. 12 sentences came from the control group and 82 sentences came from the device group.

In *device group*, we found that 42 out of the 82 sentences (51.2%) had a positive valence, with a compound sentiment score greater than 0. Participants described the amplified sounds as engaging, soothing, or pleasantly surprising. For instance, P06 described the interactive quality of the sound: *"The sound they made when you opened and closed the scissors was pretty engaging."* Similarly, P14 emphasized sensory pleasure in everyday action: *"I liked*

[2]While a significant interaction effect was observed, this result emerged only after the outlier removal process based on exploration duration, as described in Section 5.7. When analyzing the full sample of 64 participants, the interaction effect was not statistically significant, suggesting that this effect requires further validation. Detailed results for this measure, both before and after outlier removal, are provided in the supplemental materials. The removal of outliers did not affect the statistical significance of other measures.

hearing the sound of me writing on the paper with the marker" and P51 noted the calming effect of the audio:*"The brush sounds were relaxing and the strands were soft."* Several participants described how the amplification revealed previously overlooked signals. P02, for instance, observed: *"Removing the cap also sounded pretty cool – I hadn't noticed it made that sound before, but it makes a little *pop*."* P22 further reflected how these sounds affect their attitudes toward objects:*"I can see how auditory feedback could promote the creative act, simply by making us more curious about the objects we're interacting with."*

24 sentences (29.3 %) were identified as neutral in sentiment (i.e., compound sentiment score equal to 0), where participants simply described what they noticed about the objects such as their observations of the mechanical details. For instance, P12 said: *"I noticed that when I moved the mug around, there was a noise coming from inside the handle."* and P43 said: *"The scissors could be used by both hands and made a snipping sound when used."*

Not all of these sentences described positively about the sounds. 16 sentences with sound-related terms (19.5 %) were classified as having a negative valence, with the compound sentiment score lower than 0. One cause was the lack of sound in certain parts of objects. For instance, P55 said: "*The lid [of the coffee cup] made no sound when I put it on and took it off, which I thought was disappointing.*" We also observed individual differences in sound preferences. While some participants found certain sounds pleasant (e.g., P02 and P14 found the sharpie sound to be positive from previous quotes), others might have different thoughts: "*I was hoping the sharpie would make a nice sound when putting the cap on but it didn't. It also didn't sound that good when drawing either.*", said P41.

In comparison, the *control* group produced fewer reflections on the sounds overall. 4 out of 12 sentences (33.3%) had a positive valence, 4 (33.3%) were neutral, and 4 (33.3%) had a negative valence. As shown in Figure 6, a higher percentage of writings from participants in the *device group* exhibited positive valence compared to those from the *control* group.

Overall, we found that the audio augmentation delivered by our device drives attention to auditory information that would otherwise be overlooked. The majority of participants perceived these amplified sounds as either positive or neutral, though individual differences in perception were observed.

6.3 Curiosity and Exploratory Behavior

With our device drawing attention to the auditory properties of objects, another dimension we examined was whether participants exhibited a curious state while interacting with the objects. Curiosity was assessed through participants' exploratory behavior, with a focus on exploration duration and trial-and-error patterns.

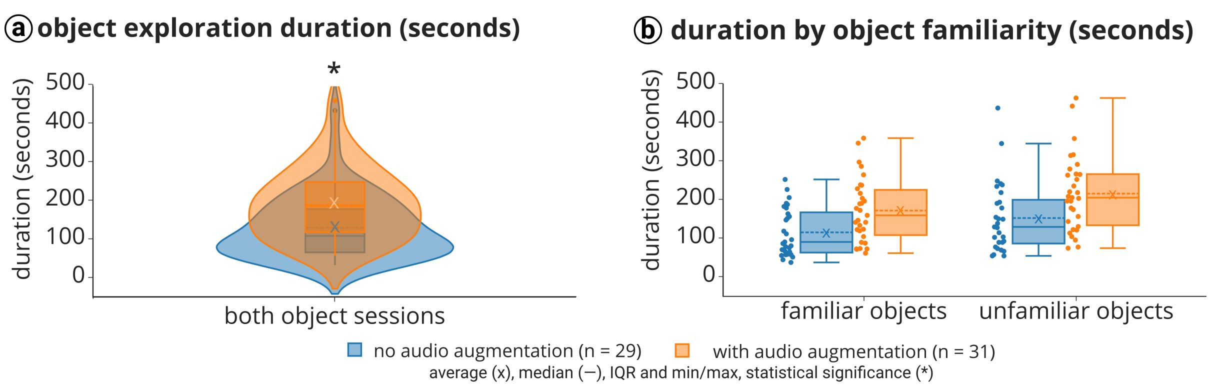

Fig. 7. Object exploration duration (in seconds). (a) Exploration duration across both sessions. (b) Exploration duration for familiar and unfamiliar object sessions.

6.3.1 Exploration Duration. We first analyzed the total amount of the time participants spent interacting with all objects, which is an indicator for epistemic curiosity in object exploration, following prior work [73]. Using a linear mixed effect model, a main effect was found for audio augmentation ($F(1,58) = 9.07, p = 0.004$). Participants with audio augmentation interacted with objects for a longer duration ($M = 193.35, SD = 91.35$) than participants without audio augmentation ($M = 133.41, SD = 78.59$). This confirms H2. A main effect was also found for object familiarity ($F(1,57) = 22.55, p = 0$). Participants interacted with familiar objects ($M = 144.02, SD = 76.99$) for a shorter amount of time than with unfamiliar objects ($M = 184.75, SD = 98.13$). However, no significant interaction between audio augmentation and object familiarity was observed ($F(1,57) = 0.11, p = 0.75$).

6.3.2 Trial-and-error Pattern. We further analyzed the participants' exploratory behavior patterns, with a specific focus on trial-and-error behaviors—characterized by repeated actions with deliberate variations [13]. This behavioral pattern suggests an active process of learning through experimentation, driven by curiosity and a desire to reduce uncertainties [36]. Figure 8 is from raw footage of the study and illustrates several examples. In Figure 8(a) and (b), a participant repeatedly opened and closed a pair of scissors, using different hands and in different directions. In Figure 8(c), a participant brushed a broom across different surfaces, such as their hand and the table. In Figure 8(d), a participant tapped a coffee cup on different locations of the table.

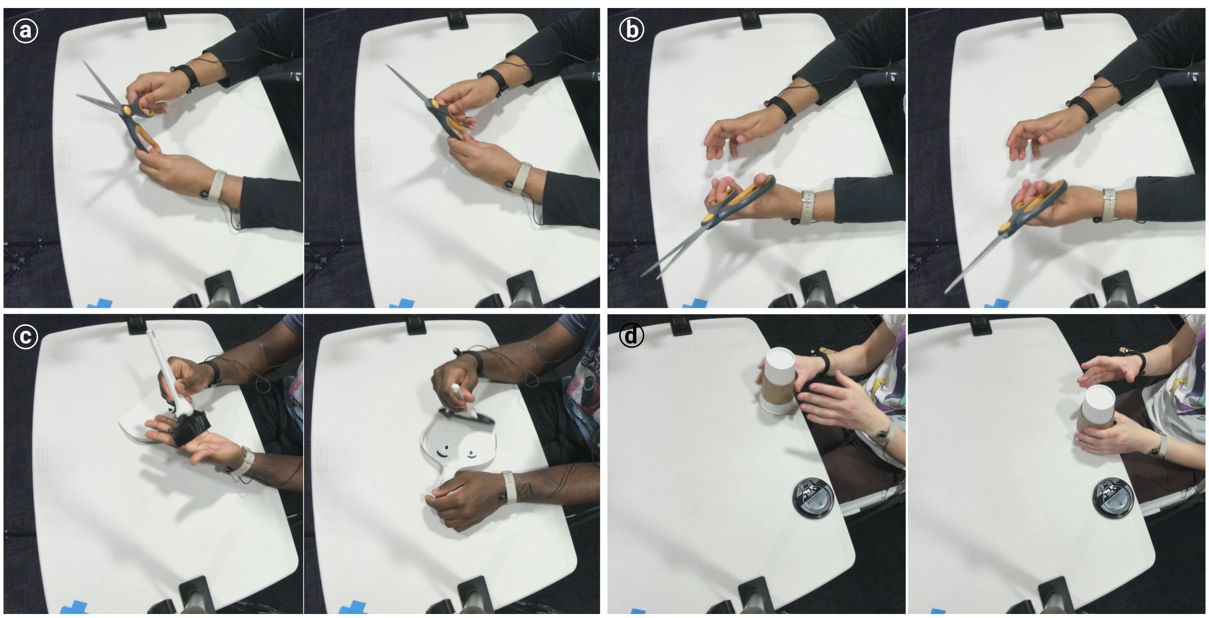

Fig. 8. Raw video footage from the study showing participants developing trial-and-error behavioral patterns. (a, b): Opening and closing the scissors with different hands. (c) Brushing on various surfaces, such as the hand and the table. (d) Knocking a coffee cup on different areas of the table.

Two coders annotated instances of trial-and-error behavior using a predefined coding schema (see supplemental materials). Trial-and-error was operationalized as the repetition of actions with at least three variations. Three variations were chosen to mitigate false-positive repeating actions not for exploratory purposes [63, 77]. In the first phase, each coder independently reviewed the data, identified potential trial-and-error patterns, and recorded the corresponding instances. After the initial coding, the coders met to compare their identified patterns, discussing discrepancies and reaching consensus on a finalized list of trial-and-error patterns. Each coder then

Table 2. Trial-and-error patterns observed in both groups across eight objects. For each pattern, the number of instances observed in each group is reported. An instance is defined as one participant exhibiting such behavioral pattern with at least three variations. For example, the first row of the table shows that five participants in the device group repeatedly opened and closed the lid tab, while one participant in the control group exhibited the same pattern.

Trial & Error Patterns in the Exploration of *Familiar* Objects

coffee cup	# in control	# in device	**storage bag**	# in control	# in device
open and close lid tab	1	5	crumble storage bag	0	4
knock coffee cup on table	0	3	zip and unzip storage bag	2	4
cap and uncap coffee cup	1	4	open and close fist in the storage bag	0	1
slide coffee cup sleeve on and off	1	7	put hand into the storage bag	0	5
smell the coffee cup	0	1	move storage bag in different directions	0	1
rub the coffee cup with fingers	0	1	slide the storage on different surfaces	0	1
tap the coffee cup with fingers	0	4	inflate and deflate the storage bag	0	0
squish the coffee cup sleeve	0	1			
total	**3**	**26**	**total**	**2**	**16**
scissors	# in control	# in device	**pen & paper set**	# in control	# in device
open and close scissors	16	26	cap and uncap pen	0	5
knock scissors on the table	0	1	tear the paper	0	1
slide scissors on the table	0	1	tap the pen on different surfaces	0	2
tap scissors with hands	0	4	bend the paper	0	3
rub scissors with hands	1	3	slide the paper on the table	0	3
total	**17**	**35**	**total**	**0**	**14**

Trial & Error Patterns in the Exploration of *Unfamiliar* Objects

handbag	# in control	# in device	**mug**	# in control	# in device
open and close the magnetic clasp	2	4	shake the mug back and forth	6	14
put hand into the handbag	0	5	put hand into the mug	2	13
rub the fabric of the handbag	1	4	tap the mug with hands	4	11
slide the bag on the table	0	1	scratch the mug with nails	1	4
tap the handbag with hands	0	2	slide the mug on the table	0	1
flick the ring behind the handbag	1	2	smell the mug	0	1
total	**4**	**18**	**total**	**13**	**44**
tape dispenser	# in control	# in device	**broom & dustpan set**	# in control	# in device
stick and unstick the tape	0	5	brush the bristles against surfaces	7	24
open and close dispenser clamp	14	24	clip and unclip the broom to dustpan	1	1
cut the tape with dispenser teeth	0	5	slide the broom and dustpan on table	0	1
scroll the tape roll	0	3	tap the broom and dustpan with hands	0	2
slide the dispenser on the table	1	1	knock the dustpan with broom	0	1
tap the dispenser with hands	0	2			
squish the tape	1	1			
total	**16**	**41**	**total**	**8**	**29**

revised their codings to align with this agreed-upon pattern set. In the second phase, the coders compared annotated instances participant by participant, resolving any remaining disagreements through discussion until full consensus was achieved.

In total, we identified 49 trial-and-error patterns across 8 objects from both groups, as shown in Table 2. For each pattern, we reported the number of instances observed in the *control* and *device* groups. Each instance of a trial-and-error pattern involved a participant repeatedly performing the action with at least three variations. We found that participants in the *device group* exhibited 223 instances of trial-and-error behavior—91 with familiar objects and 132 with unfamiliar objects. In comparison, the *control group* showed 63 instances in total—22 with familiar objects and 41 with unfamiliar ones.

A linear mixed effect model revealed a main effect for audio augmentation ($F(1,58) = 28.05, p = 0$). Participants exhibited more trial-and-error behavior when interacting with objects with audio augmentation ($M = 7.19, SD = 4.5$) than participants without audio augmentation ($M = 2.17, SD = 2.31$). A main effect was also found for object familiarity ($F(1,57) = 17.85, p = 0$). No significant interaction effect was found between audio augmentation and object familiarity ($F(1,57) = 2.01, p = 0.16$).

6.4 Agency

We analyzed the agency ratings by each item as the reliability is lower than 0.6. The items include two positive agency measures and two negative agency measures and Figure 9 shows the results for agency.

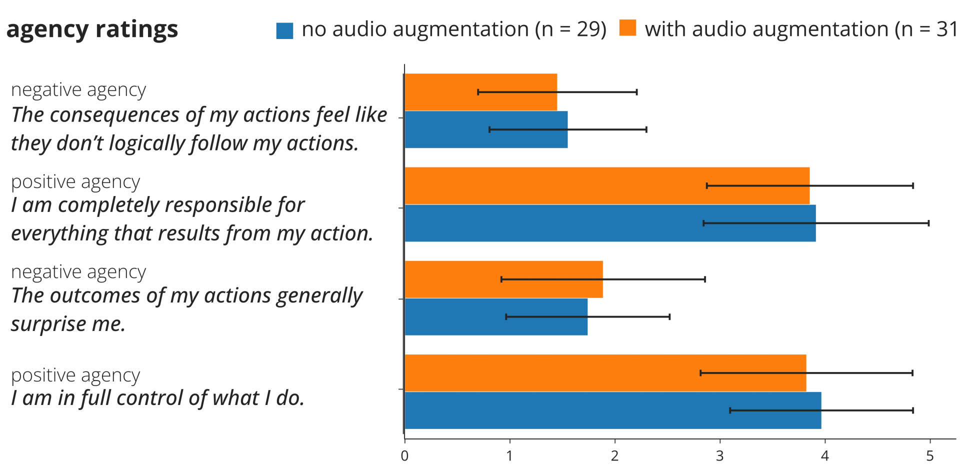

Fig. 9. Results for agency ratings by item. Item #1 and #3 (counting from the top) are negative agency items, while item #2 and #4 are positive agency items.

In the positive agency items, the analysis revealed no main effects of either audio augmentation ($\mathrm{F}(1,58) = 0.44, p = 0.51$) or object familiarity ($F(1,57) = 1.04, p = 0.31$) on the agency item *"I am in full control of what I do"*. No significant interactions were found between audio augmentation and object familiarity ($F(1,57) = 0.83, p = 0.37$) on this item either. For the other positive agency item *"I am completely responsible for everything that results from my action."*, no main effects were found in audio augmentation ($\mathrm{F}(1,58) = 0.06, p = 0.81$), object familiarity ($F(1,57) = 0.0, p = 0.97$), or interactions between the two ($F(1,57) = 0.94, p = 0.34$).

In the negative agency items, the analysis revealed no main effects of audio augmentation ($\mathrm{F}(1,58) = 0.64, p = 0.43$) on the agency item *"The outcomes of my actions generally surprise me."* but a main effect for object familiarity ($\mathrm{F}(1,57) = 5.22, p = 0.026$). Unfamiliar objects were found to introduce more surprise ($M = 1.97, SD = 0.93$) than familiar objects ($M = 1.67, SD = 0.81$). No significant interactions were found between audio augmentation and object familiarity ($F(1, 57) = 1.30, p = 0.26$) on this item. For the other negative agency item *"The consequences of my actions feel like they don't logically follow my actions."*, no main effects were found in audio augmentation (F$(1, 58) = 0.41, p = 0.53$), object familiarity ($F(1, 57) = 1.27, p = 0.26$), or interactions between the two ($F(1, 57) = 0.006, p = 0.94$).

These results indicate that while our device modified the auditory experience of the user, those in the *device group* felt a similar level of the control as those who did not receive any audio augmentation.

6.5 Awe, Affective States, and Connectedness to Objects

We further used a linear mixed effect model to analyze the auxiliary measures, including awe, affective states and connectedness with objects.

6.5.1 Awe. The analysis revealed no main effects for audio augmentation (F$(1, 58) = 1.74, p = 0.19$), object familiarity ($F(1, 57) = 0.80, p = 0.37$) or their interaction ($F(1, 57) = 0.29, p = 0.59$). Participants reported a similar level of awe between *control group* ($M = 1.64, SD = 0.58$) and *device group* ($M = 1.92, SD = 0.81$). Thus, the result did not support H3.

6.5.2 Connectedness to Objects. Similarly, no main effects were found for either audio augmentation ($F(1, 58) = 0.49, p = 0.49$) or object familiarity ($F(1, 57) = 0.85, p = 0.36$) on connectedness to objects. Participants reported a similar level of connectedness to objects they interacted with between *device group* ($M = 2.24, SD = 1.25$) and *control group* ($M = 2.48, SD = 1.55$). No significant interactions were found between audio augmentation and object familiarity on connectedness to objects ($F(1, 57) = 2.09, p = 0.15$).

6.5.3 Affective States. As for affective states, we analyzed all three dimensions: valence, arousal and dominance. For the valence dimension, no main effects were found for audio augmentation ($F(1, 58) = 0.37$, $p = 0.55$), object familiarity ($F(1, 57) = 0.90, p = 0.35$) or their interaction ($F(1, 57) = 0.22, p = 0.64$). For the arousal dimension, no main effects were found for audio augmentation ($F(1, 58) = 1.11, p = 0.30$) but a main effect found for object familiarity ($F(1, 57) = 19.60, p = 0$). Familiar objects ($M = 4.18, SD = 0.83$) evoked stronger arousal than unfamiliar objects ($M = 3.73, SD = 0.95$). No interaction effects were found between the two between audio augmentation and object familiarity ($F(1, 57) = 2.88, p = 0.1$). For the dominance dimension, no main effects were found for audio augmentation ($F(1, 58) = 0.64, p = 0.43$) but a main effect found for object familiarity ($F(1, 57) = 5.24, p = 0.03$). This means that participants felt more dominant when interacting with familiar objects ($M = 3.90, SD = 0.87$) than with unfamiliar objects ($M = 3.65, SD = 0.95$). No interactions were found between audio augmentation and object familiarity ($F(1, 57) = 0.12$, $p = 0.73$).

6.6 Post-intervention Meditation Experience

In a post-intervention task, participants engaged in an object-focused meditation exercise and reflected on their experience through a questionnaire. As an exploratory measure, we analyzed their qualitative feedback to examine whether prior exposure to audio augmentation could influence subsequent attempts to foster a mindful state by themselves.

13 out of 31 participants in the *device group* explicitly mentioned that the prior object exploration sessions with audio augmentation were helpful for their subsequent meditation practice. 7 participants noted that they were more aware of different properties of the object, even though audio augmentation was not present in this meditation. P04 described the prior exposure "primed" their mindset for meditation:"*It primed me on all the ways I could focus and consider an object...I was ready to just be considering and thinking about the sense-related stimulus from the object.*" Similarly, P39 said:"*The previous sessions also made me more aware of the possible sounds and sensations I could get from the object*". P55 further highlighted how the early experience encouraged a more active exploration of the object:"*I found my self trying to explore the object more to create sounds and audio feedback,*

which I do not think I would have done prior to the other experiences." Beyond sounds the object can generate, P51 also brought up sensory engagement of other modalities:"*I think it made me want to smell it and put it on.*"

While many participants found audio augmentation to be positively influencing their meditation experiences, one participant pointed out a potential negative effect-a disruptive after-effect:"*I think being exposed to enhanced audio from the objects in both of my previous sessions really detracted from my experience in the meditation session now. I just couldn't connect with the object I was given in the same way I was able to previously, as my actions felt so much more detached and irrelevant.*" Without explicit prompting, the remaining participants in the *device group* did not directly comment on how audio augmentation affected their subsequent meditation experience.

7 DISCUSSION

7.1 Sensory-driven Approach to Foster Everyday Mindfulness

We introduce a wearable device that amplifies sounds produced from manual actions to support mindfulness during everyday activities. Through an in-lab study with 60 participants, we found that the device increased self-reported state mindfulness during an object exploration task. Our study also measured key mechanisms of mindfulness [15]: attention and curiosity.

Regarding the attention dimension, the device modulates the salience of sounds around the user's hand by amplifying them. Our study found that this audio augmentation led participants to notice more about the auditory properties of objects. Those in the device group referred to sound-related terms nearly nine times as often as participants in the control group in a post-task questionnaire. This suggests that the device enhances users' attention to auditory information typically overlooked without such augmentation. With self-regulation of attention being a key aspect of mindfulness, our device makes sensory cues from present-moment actions more noticeable and easier for users to deliberately focus on. In the curiosity dimension, our device introduces elements of sensory surprise into ongoing interactions through audio augmentation. From the study, increased curiosity was reflected in participants' exploratory behavior during the task session. Participants in the device group interacted with objects for a longer duration compared to those in the control group. Device group participants also exhibited more trial-and-error patterns, indicating active experimentation facilitated by the audio augmentation. These results align with the curiosity orientation in mindfulness, where audio augmentation sparks curiosity and motivates users to engage more deeply with everyday interactions.

Our study also considered how object familiarity may impact the effectiveness of the device. No interaction effects were identified in most of the measures, such as self-reported state mindfulness or interaction duration. For self-reported state mindfulness, we observed consistently high ratings across all conditions (averaging above 4 on a 5-point scale), suggesting a possible ceiling effect [90]. This may be due to the structured and distraction-free nature of the in-lab setting, which likely encouraged participants to sustain a high level of focused attention throughout the task [101]. As a result, the interaction effects between audio augmentation and object familiarity may not have been able to manifest in this measure with current design. Future work should explore multi-session study to mitigate the potential ceiling effects, a possibility we will discuss further in the following sections. For the behavioral measure, prior research suggests that exploratory behavior is often driven by the intention to reduce uncertainty about objects [36]. Unfamiliar objects inherently introduce more uncertainty than familiar ones, which may explain the strong main effect of object familiarity on exploration duration. The lack of an interaction effect on interaction duration suggests that the relative level of uncertainty introduced by audio augmentation—whether interacting with familiar or unfamiliar objects—may have been similar. While an interaction effect between audio augmentation and object familiarity was found in the use of sound-related terms in object descriptions, it emerged only after the removal of outliers (at a sample size slightly lower than what predetermined through power analysis). This suggests that the effect may be sensitive to data variability and potentially underpowered. Future research should replicate this finding with larger samples to confirm the robustness of the observed interaction.

When evaluating auxiliary qualities that correlate with mindfulness, such as affective states, sense of awe, or connectedness to objects, we found no main effect in any of the measures. These results are understandable given the nature of the study design. For example, the primary study task was object exploration, which most participants described as fun. The inherently exploratory and engaging nature of the task may have naturally elevated affective states across all conditions, potentially masking any additional effects of the audio augmentation. Additionally, while sense of awe has been shown to correlate with state mindfulness [118], it is more commonly elicited by nature-based mindfulness experiences, where participants encounter something grand or vast [54]. In contrast, our study took place in an indoor lab setting, and the audio augmentation provided by our device may not have been sufficiently expansive to evoke a strong sense of awe. Last but not least, participants in both groups reported relatively low levels of connectedness with the objects, regardless of familiarity. This may indicate that the short duration of the interaction with audio augmentation might not be sufficient to foster a deeper connection with objects.

7.2 Preserving Agency in Augmented Sensory Experiences

As much as audio augmentation of manual interactions can support mindfulness, considerations around user agency must also be taken into account. This is due to the nature of such systems modifying how users perceive their actions and interactions with their surroundings. Prior work has shown that excessively intrusive signals, such as overly loud sounds or noticeable latency, can lead to discomfort [120] or a reduced sense of control [10, 107]. Considering mindfulness is a process of self-regulation of deliberate attention, preserving the sense of control is critical for technology-assisted mindfulness.

Our intention to preserve user agency informed several critical design choices in the development of our device. First, we chose to apply amplification only to sounds produced by manual interactions, rather than using other auditory manipulation techniques (e.g., reverberation). This decision ensures that the augmented signals remain close to the original sounds, maintaining their natural quality. To determine an appropriate level of audio augmentation, we drew on the domain expertise of mindfulness coaches. In a formative study with two mindfulness practitioners, we asked them to select the level of augmentation that felt most natural and supportive for everyday mindfulness. Both participants selected the same amplification level, which was subsequently implemented in the hardware.

In the in-lab study with 60 participants, we found that participants qualitatively described the augmented sensory experiences delivered by our device as "engaging" and "relaxing". In fact, over 80% of participants used at least a neutral tone when describing the sounds enhanced by the device, with the majority expressing positive sentiment. Even in responses that conveyed negative sentiment, the remarks often reflected the absence of sound in certain parts of the objects rather than dissatisfaction with the augmented auditory experience itself. Moreover, while the current hardware implementation introduces a latency of 21.3 ms, no participants reported qualitative feedback suggesting that this latency negatively impacted their experience. We also measured user agency using self-report ratings and found that participants who experienced audio augmentation reported a similar level of agency as those who did not.

While the qualitative feedback and the lack of significant differences in user agency are encouraging, further work is needed to enhance both the evaluation of user agency and the hardware implementation of the device. First, confirming the absence of effects on user agency will require a larger sample size and the use of more objective measures, such as the intentional binding paradigm [81]. A more objective understanding of how different levels of augmentation influence mindfulness is also needed, beyond relying on expertise from a small sample size of experts. Future work should determine audio augmentation level by evaluating with a larger and more diverse participant pool. For instance, psychophysical testing could help identify the perceptual intensity threshold at which audio augmentation is most effective in supporting mindfulness while preserving user agency. In parallel, future hardware prototypes could be improved to better support real-time audio augmentation. A promising direction involves further minimizing the system latency to guarantee real-time audio augmentation. For example, implementing gain adjustments at the analog level could reduce latency by bypassing computational overhead. Moreover, close microphone placement near the sound source could introduce near-field acoustic effects that distort perceived naturalness of the sounds if not properly managed. Future work could explore methods to correct for these effects or investigate alternative microphone placements—such as positioning it farther from the wrist—to help mitigate potential side effects.

7.3 Limitations

This paper serves as an initial step toward exploring audio augmentation of manual interactions to support mindfulness, and it comes with several limitations.

On the device level, while our system aims to support key components of mindfulness—attention and curiosity toward present-moment experiences—it does not address all aspects of what mindfulness entails. Specifically, in the second component of mindfulness suggested by Bishop et al. [15], it also involves an attitude of acceptance and non-judgment. Our device does not explicitly support this attitudinal dimension through a sensory-based approach and may need to be combined with instruction-based strategies to more fully cultivate this aspect.

To evaluate the device, we used an object exploration task. Multiple objects were sampled within each familiarity category to minimize the potential influence of any single auditory property on the results. However, the resulting interactions with the selected objects only represent a small set of sounds that might arise in manual interactions. Future work could consider more broadly sampling everyday objects and identifying commonalities and variances in their manual interactions sounds. This could help understand how particular sound characteristics interact with audio augmentation to influence the mindfulness outcomes.

Moreover, the object exploration task is limited in its naturalness and does not reflect the broad range of actions people engage in during everyday life. Future work should explore other everyday activities, such as journaling [27] and dishwashing [42]. In these contexts, investigating how audio augmentation impacts on perceived naturalness of the routines tasks becomes increasingly important—a dimension that was not fully examined in the current study design. Another promising direction is an at-home study, where participants take the device with them and wear it during routine tasks at will. With the device more naturally integrated into everyday interactions, future work could gain insights into the types of tasks in which it would be most helpful.

In the current study design, attention was measured indirectly by assessing how much the auditory properties of objects stood out to participants. While this measure aligns with the salience aspect that the device is designed to modulate, it does not capture how participants allocate attentional resources over time. Future work could adopt physiological measures—such as brain activity monitoring (e.g., EEG or fNIRS)—to more directly assess how exposure to audio augmentation affects attentional engagement during manual interactions.

Additionally, the study relies heavily on self-report ratings to assess various constructs, which may have contributed to participant fatigue and potentially influenced response reliability. Future research should consider reducing the number of self-report items, guided by the main effects observed in the current study, and incorporating more objective and behavioral measures to reduce the cognitive load associated with survey completion. For instance, task performance metrics, response times, or even sounds produced by manual interactions could complement self-reports and provide a richer understanding of how audio augmentation impacts on mindfulness.

From the study results, we uncovered the effect of audio augmentation on state mindfulness, as well as on two related constructs: attention and curiosity. While these results are promising, future work should more thoroughly examine the relationships among these factors, such as possible mediation effects. Although these constructs are closely aligned with being in a state of mindfulness, there may be other drivers or variables that we did not control for, which could produce similar effects. Future research should further investigate the mechanisms and theoretical foundations underlying audio augmentation of manual interactions.

Last but not least, we gauged the post-intervention effects of audio augmentation through a meditation task. However, due to the exploratory nature of the measure—qualitative self-reports—the exact aftereffects of audio augmentation remains inconclusive. Future work should consider quantitative measures to systematically assess the post-intervention effects of sensory-driven interventions on mindfulness beyond the immediate task.

7.4 Future Directions

We see valuable future directions for researchers to continue to explore audio augmentation of manual interactions to support mindfulness.

Examining long-term effects of audio augmentation. To realize the device's full impact, it is essential to understand how the short-term effects of audio augmentation on mindfulness translate into long-term benefits. An immediate next step lies in conducting multi-session studies, where participants use the device across multiple days and/or for multiple times a day, following prior work [108]. Such a study design helps reduce the novelty effect associated with initial exposure to the task or device. In these multi-session contexts, the audio augmentation device should be integrated with established mindfulness training programs, allowing researchers to assess how it supports mindfulness practice in comparison to existing state-of-the-art methods. Certain training, such as curiosity practices—where practitioners intentionally cultivate a sense of curiosity about their everyday environment—could be especially well-suited.

As with other forms of sensory input, habituation from repeated exposure must be considered in the long-term use of the device. In this context, audio augmentation may lead to a reduced response over time [94]. Multi-session studies would also allow us to examine how long the device continues to support mindfulness and how its effects fluctuate with repeated use. By understanding the habituation curve, we can then design strategies for administration of the intervention over time. For instance, one potential strategy to mitigate habituation is to deliver audio augmentation at random times throughout the day, thereby enhancing the element of sensory surprise introduced by the device. This randomized administration also helps avoid continuous exposure, which may lead to dependence on the device. Previous work on Just-In-Time Adaptive Interventions (JITAIs) [59, 64, 85] has provided valuable insights into context-aware administration of interventions, moving beyond pure randomization. For example, the device could activate selectively when mindfulness is most difficult to self-regulate, such as during episodes of emotional distress, while leaving space for self-practice of mindful awareness in other contexts.

Personalizing heightened auditory experiences. The potential of audio augmentation extends beyond the single-level amplification explored in this study. For example, each individual might have different sensitivity to sounds, suggesting that the optimal level of augmentation for supporting mindfulness should be calibrated for each user prior to use. Additionally, sounds that are perceived as pleasant by some users may be experienced as negative or distracting by others. Therefore, user preferences should be considered when deciding which sounds to amplify, rather than uniformly amplifying all audio cues as done in the current prototype. For instance, a future version of the system could activate selectively during specific activities, such as cooking or dish washing. Recent advances in user activity detection and sound classification using machine learning [78] offers great insights on how to achieve more personalized and context-aware auditory experiences.

On the other hand, different population samples may respond to audio augmentation in distinct ways and could benefit from personalized audio augmentation. In the current study, we focused on a general population—primarily healthy, young adults—as an initial step toward understanding the impact of audio augmentation. Moving forward, a more diverse sample will be necessary to better evaluate the broader potential of the device. For example, individuals who regularly practice mindfulness and exhibit higher levels of trait mindfulness may not require audio augmentation as frequently as those who are new to the practice. Additionally, individuals with attention-related conditions such as ADHD could offer valuable insights into how heightened auditory experiences are perceived, and whether such stimuli can support increased present-moment awareness in this population.

Behavioral impact of augmenting manual interactions. Hand interaction is fundamental to everyday activities and offers a window into how people understand and engage with their environments [68]. As the device continues to be explored in real-world contexts, an open question remains: how does audio augmentation influence user behavior during manual interactions? In this study, we found that audio augmentation elicited longer interactions with objects and promoted trial-and-error manipulation patterns. However, additional task-relevant metrics warrant further investigation. Future research could examine factors such as left- versus right-hand usage, the frequency of hand movements, and shifts between verbal and non-verbal gestures during device activation. Beyond object-based interactions, it would also be valuable to explore other types of manual behaviors. For instance, in interactions involving only the body—such as rubbing hands together or scratching the skin—future work could assess how audio augmentation shapes body perception.

8 CONCLUSION

In this work, we introduce a wearable device that supports everyday mindfulness through a sensory-driven approach. By augmenting sounds around the user's hands and playing them back to the user in real time, the device offers a fresh perspective on everyday, mundane interactions. In the in-lab study with 60 participants, we demonstrated the effectiveness of our device in increasing the self-reported state mindfulness during an object exploration task. Audio augmentation drew attention to auditory properties of objects that would otherwise be overlooked. Moreover, participants experiencing audio augmentation explored objects for a longer duration and exhibited more trial-and-error patterns compared to those without. Audio augmentation of manual interactions has the potential to open up new possibilities for supporting mindfulness woven into everyday activities.

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