

AirHook: Simulating Multi-directional Wind Around Ears to Enhance Presence in VR

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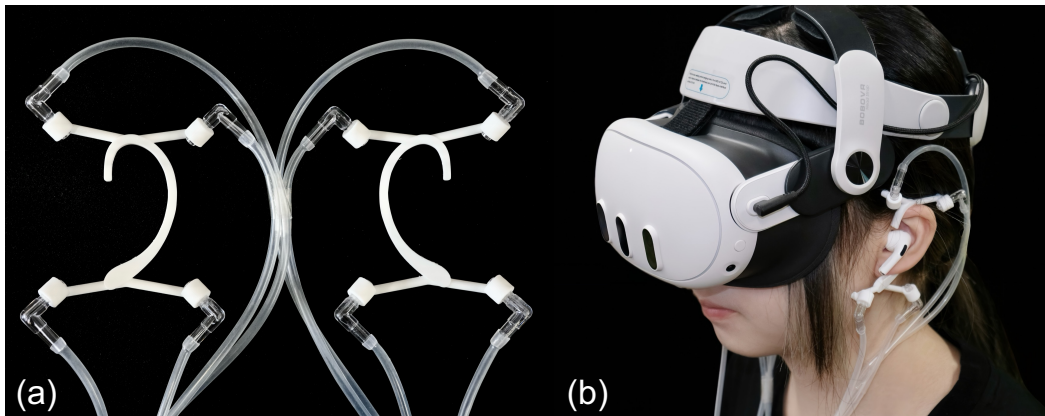


Fig. 1. AirHook Overview. (a) AirHook is an ear-hook style device that renders multi-directional wind around the ear. (b) A VR user wearing AirHook.

Bulky fan arrays and room-scale airflow systems have shown that wind can enhance presence in Virtual Reality (VR), but they are difficult to deploy and do not readily support head-worn, spatially coherent cues. We present AirHook, a lightweight ear-hook wind interface that delivers omnidirectional airflow around the periauricular region without interfering with a head-mounted display. AirHook renders spatial, dynamic 3D wind cues by activating a compact nozzle array with a head-contingent airflow rendering algorithm, enabling intermediate directions beyond discrete nozzle orientations. We evaluate AirHook in three studies: two perceptual studies respectively characterizing 3D direction recognition across stimulus durations and a 36° directional-resolution benchmark, and a VR study comparing No Wind, Non-directional Wind, and Multi-directional Wind, combining questionnaires and interviews. Results show that multi-directional wind provides additional experiential benefits beyond non-directional airflow and yields practical design implications for ear-based wind feedback.

CCS Concepts: • **Human-centered computing** → **Haptic devices**.

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ACM 2573-0142/2026/8-ARTMHCI9716

<https://doi.org/10.1145/3821687>

Additional Key Words and Phrases: Wind Feedback, Virtual Reality, Haptic Perception, Earable Design

ACM Reference Format:

Yuxuan Sun, Tian Min, Liwei Chan, Takashi Amesaka, and Yuta Sugiura. 2026. AirHook: Simulating Multi-directional Wind Around Ears to Enhance Presence in VR. *Proc. ACM Hum.-Comput. Interact.* 10, 5, Article MHCI9716 (August 2026), 26 pages. <https://doi.org/10.1145/3821687>

1 Introduction

Virtual Reality (VR) systems provide an immersive experience for users primarily through audiovisual presentation on head-mounted displays (HMDs), further enhanced by vibrational feedback through handheld controllers. While these modalities place the baseline of information convey and interaction enhancement from commercial-off-the-shelf (COTS) devices, the immersion they offered is still limited compared to the capability of ideal VR systems that create richer and more realistic virtual worlds [8]. Ongoing research has been exploring more comprehensive sensory modalities for VR systems, in order to provide a more complete experience in both perception and interaction, which is more similar to reality. For example, the use of haptic cues [9, 12, 63], thermal feedback [18, 51, 61], or locomotion interfaces [39] that align with the audiovisual information in the HMD.

Among the methodologies improving the level of immersion, *Wind*, as a natural source of haptic perception that is pervasively experienced in everyday environments, has been widely adopted as an enhancement in VR systems [10, 46, 47, 52, 54, 60]. The integration of airflow cues offers unique advantages for enhancing VR immersion. Technically, it is a cost-effective, non-intrusive, and contactless modality that can be easily integrated into existing setups. From a perceptual standpoint, wind provides critical cues that are intrinsically linked to our daily experiences, which could strengthen the sense of presence and provides an effective sensory modality for conveying environmental factors (e.g. events, weather, temperature) [10, 19, 20, 25, 26, 29, 33] and motion status (e.g. walking, running) [7, 11, 44, 60, 62]. Its dynamic nature and direction representation further make it a versatile tool for VR designers [58]. These benefits position wind not merely as an additive effect, but potentially as another fundamental component for next-generation immersive systems in various applications [21, 54, 66].

However, most wind solutions are limited either by their cumbersome setup or by compromising the portability with advanced features (e.g., less realistic simulations). One of the prevailing approaches is through employing room-scale fan arrays [13, 25, 47, 58, 60]. Such systems are capable of rendering continuous variations and complex flows of natural wind, but often trade off with their bulky mechanical setups, spatial requirements, and high costs. To address such limitations, researchers have been exploring the alternative of attaching miniaturized fans [7, 52, 53, 66] or air nozzles [43, 54] to the HMDs, which take advantage of the high sensitivity of facial skin perceiving airflow. The development of these head-mounted devices is often constrained by the ergonomic cost of mechanical complexity, which can trigger rapid fatigue [66]. However, simplifying the setup by reducing wind nozzles sacrifices the richness of haptic experience, leading to a sparse and less authentic directional mapping.

In this study, we introduce AirHook (Fig. 1), a novel ear-worn haptic interface designed to provide localized, multi-directional wind feedback in VR. AirHook leverages the high tactile sensitivity of the pinna (the external ear) and periauricular region (the area surrounding the external ear) to airflow [36, 54], enabling the delivery of high-fidelity spatial wind cues through a remarkably compact device. By adopting a familiar ear-hook form factor, the system ensures a non-obtrusive, wearable profile that allows for omnidirectional airflow contact without interfering with the standard footprint of VR HMDs. Furthermore, the head-mounted nature of AirHook facilitates

seamless synchronization between airflow rendering and the user's head orientation via HMD-integrated sensing. To evaluate the technical efficacy and experiential impact of AirHook, we conducted three user studies. The first two studies characterized the system's *spatial resolution*, investigating users' ability to recognize 3D wind directions at a 36° granularity and examining the influence of stimulus duration on recognition accuracy. The third study assessed the *ecological validity* of AirHook by integrating its multi-directional wind feedback into diverse VR scenarios. We evaluated how our system enhances users' sense of presence and enjoyment compared to baseline conditions (no wind and non-directional wind), demonstrating its potential to significantly enrich immersive experiences. The contributions of this paper are as follows:

- We introduce AirHook, a lightweight ear-hook airflow interface that renders ear-centered, multi-directional wind cues around the ear for VR.
- We empirically characterize AirHook's 3D directional perception, including stimulus-duration effects and achievable directional resolution (using a 36° benchmark and intermediate-direction rendering).
- We show in a VR study (No Wind vs. Non-directional Wind vs. Multi-directional Wind) that multi-directional wind yields additional experiential benefits beyond non-directional airflow, and we derive design implications for ear-based multi-directional wind feedback.

2 Related Work

The development of wind interfaces in VR has evolved from ambient, room-scale installations towards personalized, wearable solutions that prioritize directional precision and portability. To situate AirHook within this landscape, we review prior research across three key dimensions: *room-scale wind displays* for environmental immersion, *wearable wind systems* for localized feedback, and the emerging field of *earable haptics*, which leverages the unique sensory affordances of the periauricular region.

2.1 Room-scale Wind Displays

Room-scale airflow systems are capable of providing full-body wind feedback, which has been used to simulate virtual environmental conditions such as thermal variations [19, 20, 25], storm events [33], and outdoor activities in VR such as sailing [60] and scooter riding [11]. Most existing systems have employed arrays of fans distributed around the user [13, 16, 37, 47, 60] to present multi-directional wind in a 3D space, or position a fan system in front of [11, 21, 33, 34] or above [19, 20, 44] the user to generate single-directional airflow. Beyond these classic configurations, prior work has explored two complementary solutions to improve the practicality and flexibility of room-scale wind display. Ito et al. [27, 28] leveraged cross-modal techniques to evoke multi-directional wind perception using two installed fans. WindyWall [58] modularized the fan-array structure into reconfigurable panels to support exploration across a broad range of wind simulations.

By simulating ambient wind around the user, room-scale wind displays can bridge the physical world and the virtual environment, thereby strengthening users' sense of presence in the scene [47, 60]. Likewise, thermal airflow effects can make environmental transitions feel physically grounded and reinforce users' sense of being situated within the virtual environment [19, 20, 25, 26, 55].

However, these systems face substantial constraints due to their dependence on fixed installations and bulky mechanical infrastructures, limiting deployment mainly to research-oriented workspaces or exhibition contexts. Wind rendering across room-scale spaces can incur high computational demands [47], and also suffers from common issues such as motor cooling [48] and latency in airflow generation [13], complicating the realization of real-time feedback in VR systems. The

need to position large-scale airflow emitters in proximity to the user further introduces challenges related to ambient noise, visual distraction, and user comfort.

This paper aims to find a balance between the deployability of the wind display and its responsiveness in VR. We target this balance by avoiding cumbersome setup procedures and supporting immediate use upon wearing, while enabling real-time synchronization with other sensory modalities in VR experience.

2.2 Wearable and Head-mounted Wind Interfaces

Recent work has explored wearable wind displays as an alternative to room-scale fan installations, aiming to make wind feedback more portable, configurable, and deployable as feedback solutions. These systems differ not only in form factor, but also in the body region they stimulate and the type of wind experience they support.

One line of work attaches wind-related actuation to the body. Recent systems have distributed actuators across multiple body regions to evoke full-body wind sensations [46], or on the wrist [23, 31, 38, 56], and hand [1] to deliver localized wind stimulation or propulsion force feedback. These studies demonstrate the feasibility of wearable airflow feedback, but their stimulation sites and interaction goals differ from the rendering of spatial wind cues around the head.

Another common implementation strategy is to deploy actuation as integrated attachments to the HMD [7, 54, 62, 66], avoiding reliance on room-scale infrastructure while maintaining spatially expressive airflow. Within this headset-attached direction, HeadMounted Wind [7] encoded airflow as a direction–speed vector and mapped it to eight fan actuators mounted around the HMD to render head-scale wind. VaiR [54] animated wind sources from multiple directions on a head scale using light, faster-reacting pneumatic nozzles and rotatable bow structures, enabling a more dynamic and mobile 3D wind presentation. AirWhisper [66] emphasizes wearability and portability, as well as modularity, combining micro fans and swappable arms to deliver compact directional airflow.

These systems highlight a recurring design trade-off: rendering more wind directions generally requires more airflow resources. To move beyond a ground-parallel plane and convey three-dimensional cues, current head-mounted solutions rotate nozzle arrays with extra motors [54]. However, the vertical sweep of rotatable structures was limited to 270° rather than a full 360° due to constraints imposed by neck anatomy, and part of the face was also occluded by the VR glasses and could not be fully exposed to frontal airflow. Our ear-centered design aims to avoid such limitations common to head-scale wind displays and ensure omnidirectional airflow contact without blind spots.

Moreover, while mounting mechanics on the HMD eliminates the need for bulky installation and reduces environmental distraction, it increases load and pressure on the users' head and face, thereby possibly causing discomfort and even fatigue after prolonged use [66]. Even if the weight of the head-mounted helmet is seriously controlled, the need to carry mechanical components for airflow generation unavoidably constrains its potential in VR experience [54]. Our system therefore aims to reduce added wearing burden by decoupling airflow generation from the wearable element and avoiding HMD-dependent structural support.

In general, wearable wind displays have also been reported to enhance presence [52–54, 57, 64], enjoyment [31, 32, 54, 59], realism [43, 54, 59, 66], and immersion [7, 32, 43, 59]. Our approach aims to extend the 3D expressiveness of airflow within a compact ear-worn form factor while minimizing on-head load.

2.3 Haptic Feedback and Interaction on Earables

Prior work suggests that the ear-centered region is a promising site for haptic feedback because users can reliably perceive subtle stimuli around the ear [24, 35]. This sensitivity also extends to airflow perception around the ear. Kojima et al. [36] showed that the skin around the ear is highly sensitive to wind perception and can support highly localized perception of wind direction. Complementing this, users of VaiR [54] further noted the high sensitivity of near-ear air streams, and adjacent facial skin (e.g., the cheek) has also been reported as among the most sensitive body locations under clothing [40]. Together, these findings motivate earables as a perceptually effective interface for spatially informative feedback.

Building on this premise, the use of earables (ear-worn devices) has expanded beyond audio playback to haptic output, establishing a compact, private, and versatile site for an evolving feedback modality. Previous studies have placed vibrotactile modules [3, 6, 17, 41, 45] and thermal modules [49, 50] in the ear-centered region for directional information transfer. FlexEar-Tips [2] introduces an in-ear haptic approach that pneumatically actuates ear tips to adjust their size. VWind [22] integrated thermal and vibrational stimuli into over-ear headphones without increasing wearing complexity in VR, while keeping electronics unobtrusive. Earables offer a distinct advantage for VR because over-the-ear placement does not conflict with headset fit, and their small, lightweight form factors avoid adding a wearing burden.

Taking advantage of the ear's high sensitivity to airflow, our work partitions the ears into multiple localized zones to demonstrate 3D spatial wind cues comparable to head-scale wind simulations. We investigated the perceptibility and directionality of ear-centered airflow, with the goal of advancing presence in VR and revealing new possibilities for earable haptic interfaces.

3 AirHook

To provide high-fidelity 3D spatial wind feedback within a wearable and non-obtrusive form factor, we developed AirHook, a distributed haptic system that leverages the anatomical advantages of the periauricular region. The system is architected to decouple heavy airflow generation components from the user's head, thereby reducing on-head load and improving wearability. AirHook consists of a pneumatic supply unit (Fig. 2) and a pair of 3D-printed ear hooks integrated with a multi-nozzle array (Fig. 3). The pneumatic supply unit can be deployed in multiple configurations depending on usage context, including placement as a stationary module (e.g., on a nearby desk or floor) or potentially as a body-worn unit (e.g., attached to the waist or belt), enabling both tethered and mobile use scenarios. The ear hooks serve as the lightweight actuation interface, delivering spatial airflow cues around the ears while maintaining compatibility with head-mounted displays.

3.1 Wind Source and Control

For the wind source, we chose 12 V vacuum air pumps (AP520B-120) for their capability of instant response with no start-up or cool-down delays. The AirHook system uses eight pumps, each of which is driven by a MOSFET Driver Module (XY-MOS) via pulse-width modulation (PWM) to control airflow independently. A 1N5408 (3 A) rectifier diode is wired in reverse bias across each pump to clamp the turn-off voltage spike and protect the driver modules from inductive kickback. Electronics are organized in two mirrored groups, each consisting of four air pumps and four driver modules to provide airflow for each side of the ears (Fig. 2a). Each group is controlled by one Arduino Uno board and powered by an AC adapter (12 V/2 A). As shown in Fig. 2b, all electronic components mentioned above are currently housed in a polyethylene case. Two pieces of soundproofing urethane foam sponge with a thickness of 3 cm are placed above and below the electronic components to reduce noise caused by the vibration of the pumps. The whole case weighed around 2.5 kg.

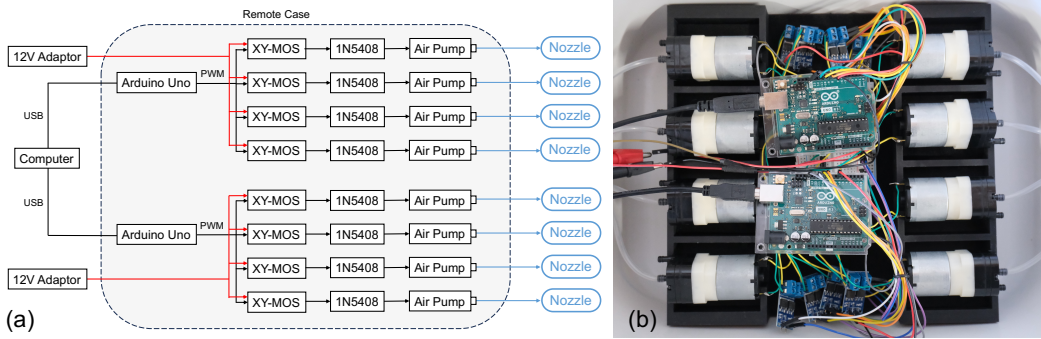


Fig. 2. (a) Block diagram of the mechanical setup for AirHook. (b) Top-down view of the pneumatic supply unit showing the internal layout of electronic components.

3.2 Ear-mounted Display

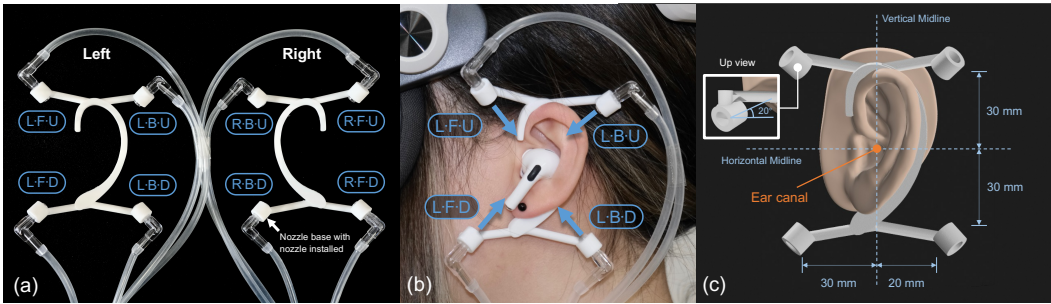


Fig. 3. (a) 3D-printed ear hooks labeled using a head-centered 3D coordinate system (L/R = Left/Right, F/B = Front/Back, and U/D = Up/Down); for example, L-F-U denotes the left-front-up nozzle. (b) Left-side view of AirHook worn on the ear, showing airflow emitted from each labeled nozzle along diagonal directions. (c) Parameterized nozzle placement relative to the ear canal and ear-hook midlines.

The wearable display of AirHook is implemented as a pair of symmetric ear hooks (Fig. 3a), adopting the familiar form factor of ear-hook earphones to achieve stable, lightweight attachment while preserving compatibility with standard VR HMDs. Following anthropometric data on average ear size for adults aged 18–30 [30], each ear hook measures approximately 65 mm in length, 30 mm in breadth, and 4.4 mm in thickness. To reduce occlusion of the skin surface and maintain airflow contact around the periauricular region, the ear hook incorporates a 2 mm-wide through-slot along the post-auricular groove.

To deliver spatial wind cues around the ear with minimal mechanical complexity, each ear hook integrates four cylinder-shaped nozzle bases (outer diameter 9.6 mm; inner diameter 5.6 mm), connected by a 4 mm-diameter cylindrical support. As shown in Fig. 3b, these nozzle bases are arranged in the plane orthogonal to the interaural axis and oriented along the diagonals of the head-centered horizontal and vertical axes. We label them using the head-centered 3D coordinate system (L/R = Left/Right, F/B = Front/Back, and U/D = Up/Down); for example, L-F-U denotes the left-front-up nozzle. Compared to aligning nozzles with cardinal axes, diagonal placement better avoids occlusions from the upper helix area that is often partially covered by hair, while still

supporting directional differentiation in both vertical and horizontal dimensions. The nozzle layout was designed to balance coverage and comfort around acoustically sensitive regions.

Figure 3c illustrates the nozzle layout relative to the ear canal, with the key geometric offsets and tilt angle annotated. Considering the relatively lower airflow sensitivity of the post-auricular area [36], the posterior nozzle pairs (L|R-B-U|D) are positioned closer to the ear with an approximately 20 mm perpendicular offset from the ear hook's vertical midline. As airflow-generated noise may be acoustically amplified near the ear canal [4], the anterior pairs (L|R-F-U|D) are placed farther outward with an approximately 30 mm perpendicular offset. Across all four nozzle bases, the radial offset from the ear hook's horizontal midline is approximately 30 mm. Each nozzle base is additionally tilted inward by 20° toward the skin to increase the effective contact area.

Air is delivered through eight L-type plastic tube connectors inserted into the nozzle bases, each connected to a silicone tube (inner diameter 3 mm; outer diameter 4 mm) routed to the corresponding air pump in the pneumatic supply unit. Our current setup uses 1.8 m tubing, allowing approximately 1.6 m of movement range for seated or standing VR experiences, and can be extended by inserting L-type tube connectors.

All ear hooks are 3D-printed in PLA, and their 3D models are provided as supplementary material in STL and STEP formats. A standard-size ear hook weighs 11.5 g with nozzles installed. To accommodate variability in ear size and fit, we prepared scaled variants at 83 % and 120 % of the standard length and breadth (10.2 g and 12.7 g, respectively). Since the inner diameter of all nozzle bases remains 5.6 mm across sizes, ear hooks can be swapped while reusing the same nozzles, supporting modular fit across users.

3.3 Airflow Rendering Algorithm

To render the wind from the virtual scene to reality, we propose an algorithm that transforms VR wind parameters into control signals for AirHook in real time. Airflow generated through AirHook is described by direction and intensity.

Direction. The direction is computed by the virtual scene's world-frame wind vector and the user's head rotation (obtained through HMD's orientation). The wind perceived by the user in the virtual scene could be caused by: (1) the environmental wind that naturally occurs; (2) the movement of the main camera (user), producing wind opposite to the movement direction; (3) the movement of a virtual object, producing wind directed from the object toward the user's head. This perceived wind direction vector under the world frame is denoted as $\mathbf{V}_{World}$. This perceived wind direction is transformed into a head-frame unit vector $\mathbf{V}_{Head}$ with the inverse head rotation R_h^T :

$$\mathbf{V}_{Head} = \frac{R_h^T \mathbf{V}_{World}}{\|R_h^T \mathbf{V}_{World}\|}$$

The head-frame wind vector $\mathbf{V}_{Head}$ is then projected onto the eight nozzles on the Ear-mounted Display. Based on the octant in which each nozzle i is located within the head coordinate system (Fig. 4a), we assigned it a fixed unit vector $\mathbf{n}_i$, pointing inward to the center of the head along the corresponding diagonal direction:

$$\mathbf{n}_i \in \left\{ \frac{(\pm 1, \pm 1, \pm 1)}{\sqrt{3}} \right\}$$

The projection coefficient c_i between the perceived wind direction vector $\mathbf{V}_{Head}$ and each nozzle's assigned direction vector $\mathbf{n}_i$ is computed by taking their dot product:

$$c_i = \max(0, \mathbf{V}_{Head} \cdot \mathbf{n}_i) \quad \text{where } c_i \in [0, 1]$$

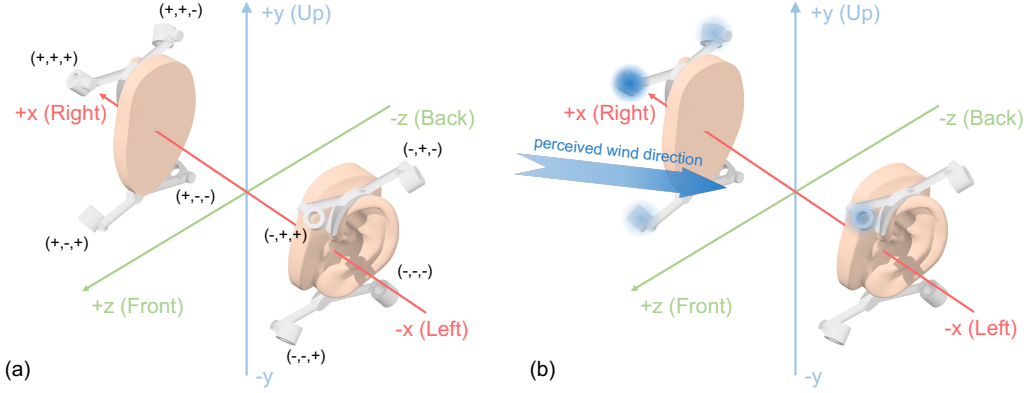


Fig. 4. (a) Nozzle locations in the head coordinate system, where each nozzle is labeled with a sign triple $(\pm, \pm, \pm)$ denoting the signs of the (x, y, z) components of each nozzle's assigned unit vector $\mathbf{n}_i$. (b) Example nozzle activation for a perceived wind direction coming from the right-front-up: highlighted nozzles are activated, with color intensity reflecting the relative projection coefficient c_i .

Negative dot products are clamped to zero so that nozzles pointing away from the perceived wind direction do not contribute to airflow generation. Fig. 4b illustrates an example of nozzle activation resulting from projecting the perceived wind direction onto the nozzle assigned direction vectors.

Intensity. Finally, the wind velocity assigned to each nozzle V_i is obtained by multiplying its projection coefficient c_i , the defined intensity of the virtual wind $I \in [0, 1]$, and its maximum wind velocity $V_i^{\max}$ obtained from a calibration process:

$$V_i = c_i \times I \times V_i^{\max}$$

We then convert this computed velocity V_i into a PWM value PWM_i using the pre-measured velocity–PWM mapping (Fig. 5a). The PWM value PWM_i is sent via serial communication to the Arduino Uno board to which the nozzle i is connected.

3.4 Technical Evaluation

To characterize AirHook's physical output and ensure safe and controllable operation for subsequent studies, we conducted two technical evaluations: (1) measuring the wind velocity produced by each nozzle as a function of PWM input, enabling consistent airflow rendering through calibrated control; and (2) measuring the acoustic output at the ear under representative operating conditions, which is particularly important because the nozzles are positioned near the ear canal.

Wind Velocity. We measured the wind velocity output from a nozzle using a thermal anemometer (Testo 405i) positioned 2 cm from the nozzle outlet, approximating its distance to the skin during use. For each nozzle, we varied the PWM duty cycle from 0 % to 100 % in steps of 10 % and recorded the corresponding wind velocity in m/s. The resulting data were fitted with a linear model, as shown in Fig. 5a, and used to construct a mapping from assigned wind velocity to PWM signal.

System Latency. Since AirHook places the actuation unit externally, we quantified system responsiveness by measuring end-to-end airflow latency from an update of HMD orientation in Unity to an airflow change detected at the ear. We positioned a microphone at the center of the right ear hook and used the onset of airflow-induced acoustic change as the detection point. Across 30

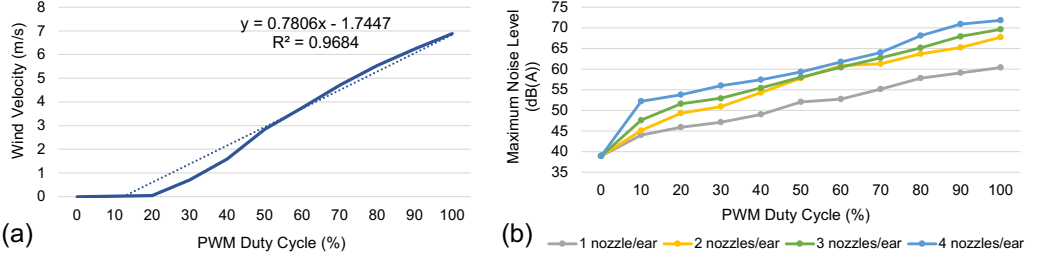


Fig. 5. (a) The mapping from pulse-width modulation (PWM) duty cycle (x , %) to wind velocity (y , m/s) for one nozzle. The dotted line indicates the linear fit, and $R^2 = 0.9684$ indicates a strong linear fit to the measured data. (b) Noise measurement results: PWM versus Maximum Noise Level (dB(A)), measured under symmetric activation of 1–4 nozzles per ear.

trials, the average latency was 112.5 ms (SD = 24.8 ms), reflecting the propagation delay from HMD sensing to the actual airflow hitting the skin.

Noise Level. Noise becomes a concern in this ear-based design because air nozzles are placed close to the ear canal. We measured noise at the ear emitted by airflow exiting the nozzles to determine the maximum PWM duty cycle for air pumps, and hence prevented users from hearing loss.

The measurement was carried out in a quiet room, with the pneumatic supply unit and ear hooks placed on a table. The pneumatic supply unit was positioned approximately 1 m away from the ear hooks, consistent with the spatial setup used in our user studies. Two ear hooks were placed 20 cm apart, reflecting their shortest possible distance during VR interactions. A sound level meter was positioned at the center of the right ear hook. We measured A-weighted sound pressure level (dB(A)) with a slow averaging setting and recorded the maximum value for each condition. Both ear hooks were driven symmetrically with identical nozzle activations. We swept PWM duty cycles from 0 % to 100 % in steps of 10 %; for each duty cycle, we tested all symmetric nozzle-activation patterns involving 1–4 simultaneously activated nozzles per ear hook and reported the maximum measured noise level, as shown in Fig. 5b. Following a public-facing safe-noise guideline [14], we capped the maximum duty cycle at 80 % to keep the sound pressure level at the ear below 70 dB under the worst-case operating condition (i.e., four nozzles activated simultaneously on each ear hook).

4 User Evaluation

4.1 Overview

The design of AirHook raises two practical questions for VR applications: (1) whether users can reliably perceive the direction of brief wind cues delivered around the ears, and (2) whether such multi-directional wind feedback yields measurable benefits in VR experience beyond simply "having wind". To answer these questions, we conducted three studies. **Study 1 and Study 2** quantify perceptual performance in controlled direction-recognition tasks, respectively focusing on how stimulus duration affects directional accuracy and whether users can localize intermediate wind directions rendered via *multi-nozzle blending*. **Study 3** evaluates AirHook in interactive VR scenes, comparing multi-directional wind feedback with no wind and non-directional wind feedback.

All studies were approved by the ethics review committee at the authors' institution. Written informed consent was obtained from all participants, who received compensation of 10 USD per hour after completing each session.

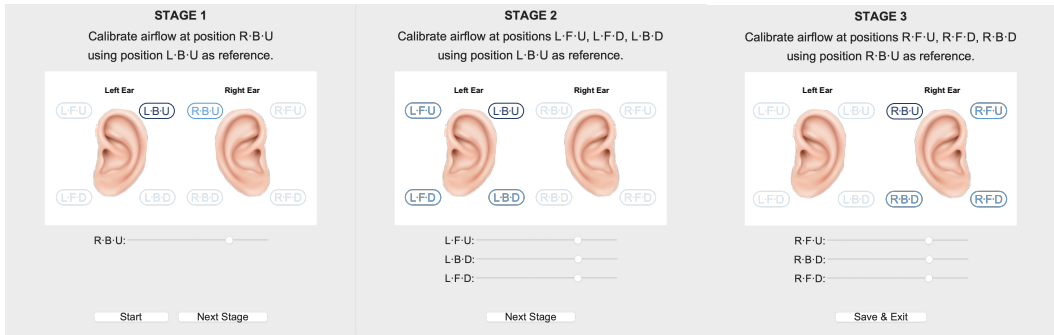


Fig. 6. User Interface for calibration process from stage 1–3. Labels such as L-B-U denote nozzle locations (L/R = Left/Right, F/B = Front/Back, and U/D = Up/Down). Participants start the process by pressing *Start*. In each stage, they match perceived airflow intensity at the nozzle(s) labeled in light blue to the reference nozzle labeled in dark blue by adjusting the slider(s). Participants press *Next Stage* to proceed and *Save & Exit* to finish.

4.1.1 Participants. There were 24 participants in Study 1, Study 2, and Study 3, respectively. All the participants involved in this study are recruited from the university, and reported normal hearing without known tactile impairments. The standard-size AirHook fitted all participants.

The participant samples were largely overlapping: Study 1 and Study 2 differed by three participants due to unavoidable participant availability, while Study 2 and Study 3 were conducted with the same 24 participants.

We adopted this partially overlapping multi-session design to reduce participant-level variability that is relevant for an ear-worn airflow interface, including differences in ear geometry, device fit, periauricular skin exposure, and sensitivity to airflow. At the same time, all sessions for a given participant were scheduled at least one day apart to reduce potential learning or carryover effects. This risk and its mitigation through the study design are further discussed in Limitations (Section 6).

4.1.2 Calibration. Because AirHook’s eight nozzles target different periauricular skin regions, and airflow sensitivity varies around the ear [36], we performed a per-participant calibration before each study to reduce intensity-related confounds in directional perception. The calibration procedure lasted approximately 2 minutes.

Based on our noise measurement under the worst-case configuration (all four nozzles on one ear activated simultaneously), we initialized the PWM value of all nozzles to 80 % duty cycle to keep operating noise within a conservative safety range. We selected L-B-U and R-B-U as reference nozzles because the upper-back region around the ear is reported to exhibit relatively low wind sensitivity [36] and therefore typically requires a higher PWM to achieve the same perceived airflow intensity. During calibration, the PWM value of L-B-U was fixed at 80 % duty cycle as a baseline reference. The calibration consisted of three stages: (1) matching perceived airflow intensity at R-B-U to the reference L-B-U; (2) matching L-F-U, L-F-D, and L-B-D to L-B-U; and (3) matching R-F-U, R-F-D, and R-B-D to R-B-U. Participants completed the stages sequentially using the interface shown in Fig. 6 and a touchpad input. In each step, the reference nozzle and the nozzle under calibration delivered airflow simultaneously. Participants adjusted the PWM of the nozzle under calibration via a slider (range 0–100 %) until both airflow sensations were perceived as equally strong.

This procedure equalized perceived intensity across nozzle locations while preserving the directional configuration. We stored the calibrated PWM values for all nozzles and converted them

into corresponding wind velocities using the linear PWM–velocity mapping (Fig. 5a). These velocities were used as nozzle-specific maximum outputs in our airflow rendering algorithm during subsequent tasks.

4.2 Study 1: Effect of Stimulus Duration on Direction Recognition

AirHook is designed for interactive VR scenarios where wind cues may appear as short events (e.g., gusts, object pass-by, or brief directional prompts). In such cases, *stimulus duration becomes a key practical parameter*: shorter cues reduce disruption and improve responsiveness, but may also reduce directional discriminability. Therefore, before evaluating higher-resolution 3D wind directions in Study 2, we first examined whether wind stimulus duration systematically affects direction recognition performance and identified representative durations for subsequent experiments.

4.2.1 Experiment Overview & Setup.

Design. We used a within-subject design that varied **stimulus duration** from 1 s to 10 s in 1 s increments, while testing recognition across six canonical 3D directions ($\pm X$, $\pm Y$, $\pm Z$). This design isolates the effect of duration under a controlled set of axis-aligned stimuli.

Apparatus. Participants wore AirHook while seated on a swivel chair. To minimize potential auditory cues from device operation, participants wore AirPods Pro to record the head rotation with noise cancellation enabled, and listened to looping pink noise throughout the task. A wireless mouse was provided to participants for button control. The identical apparatus are also used in Study 2 (Section 4.3).

Participants & Procedure. We recruited 24 participants (16 male, 8 female), aged between 19 and 29 ($M=23.9$, $SD=2.83$). After completing the calibration procedure described in Section 4.1.2, participants performed a Direction Recognition Test consisting of 60 trials (6 directions $\times$ 10 duration levels) presented in randomized order. At the start of each trial, participants initiated wind playback with the left mouse button and were instructed to face forward until the stimulus ended. We then recorded the starting head orientation and asked participants to rotate their head toward the perceived wind direction and confirm their response via a button press (right mouse button), at which point we recorded the ending head orientation. Participants returned to a forward-facing posture before proceeding to the next trial. The test lasted approximately 20 minutes, with a 1-minute break halfway through.

4.2.2 Results. To evaluate directional recognition performance, we computed the participant's perceived wind direction from the change in head orientation in each trial. This also reflects how users naturally indicate spatial directions in VR [65] and aligns with our head-centered airflow rendering algorithm. Specifically, we obtained the relative head rotation by subtracting the starting head orientation from the ending head orientation (pitch/yaw), and converted it into a 3D unit direction vector in the head frame, which served as the perceived wind direction $\hat{\mathbf{v}}_{\text{perc}}$. We then measure its agreement with the ground-truth direction $\hat{\mathbf{v}}_{\text{gt}}$ using cosine similarity and converted it to the 3D angular error θ (in degrees):

$$\theta = \arccos(\text{clip}(\hat{\mathbf{v}}_{\text{gt}} \cdot \hat{\mathbf{v}}_{\text{perc}}, -1, 1)) \times \frac{180}{\pi},$$

Figure 7 reports the group mean 3D angular error for each stimulus duration with 95% confidence intervals across participants, together with individual participant mean data points, based on per-participant mean errors averaged over the six tested directions.

We next examined whether wind display duration (1–10 s) systematically influences participants' directional recognition accuracy. Since the dataset consists of trial-level repeated measures (multiple

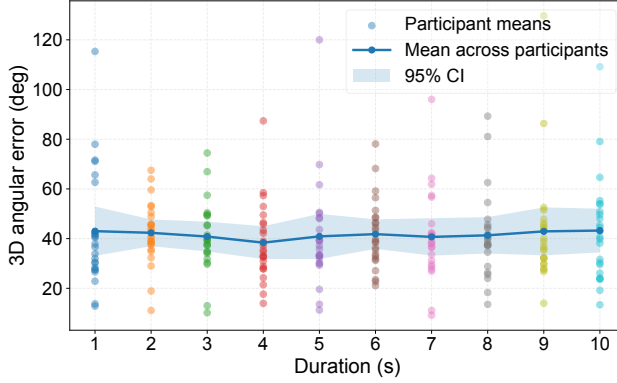


Fig. 7. Group mean 3D angular error across stimulus durations (mean of per-participant mean errors across the six tested directions), with 95% confidence intervals across participants; dots show individual participant means.

trials per participant and per direction), we used a linear mixed-effects model to account for both within-participant dependencies and direction-specific variability. The model included duration as a fixed effect, a random intercept for participant, and direction modeled as a variance component. The fitted model did not indicate a reliable change in 3D angular error with increasing duration ($\beta = 0.100$ deg/s, 95% Confidence Interval $[-0.366, 0.567]$; $N = 24$, 1440 trials). Consistently, comparing the full model against a baseline mixed-effects model without the duration term showed no significant improvement in fit (likelihood-ratio test: $\chi^2(1) = 0.172$, $p = 0.678$).

Taken together, these results suggest that within the tested range (1–10 s), directional recognition performance remains broadly stable—indicating that AirHook can support brief wind cues without requiring long exposure durations to achieve recognizable 3D direction perception. However, we observed that the 1 s duration exhibited the largest between-participant variability ($SD = 23.500$) and the widest 95% Confidence Interval (width = 19.846), suggesting that extremely short cues may lead to less consistent perception across users.

4.3 Study 2: Understanding user perception of 3D wind directions

Study 1 showed that directional recognition accuracy does not reliably improve with longer stimulus durations within 1–10 s, but the 1 s condition exhibited the largest between-participant variability. Based on this observation, Study 2 focuses on the two shortest durations beyond 1 s (2 s and 3 s) and evaluates directional recognition at a finer sampling of 3D directions. Although AirHook has a limited set of fixed nozzle outlets, it can approximate *intermediate* 3D wind directions by activating multiple nozzles simultaneously with different intensities. Study 2 therefore examines how well users can localize these *blended* wind directions, which directly addresses our goal of understanding AirHook’s practical directional resolution under a compact hardware layout.

4.3.1 Experiment Overview & Setup.

Design: 36° Directional Sampling as a Benchmark. To evaluate recognition under a denser directional sampling, we adopted the 36° division used in the VaiR system [54], where 36° corresponds to the angular spacing of its nozzle arrangement. Using this benchmark allows us to test whether AirHook can support a comparable level of directional granularity without requiring dense nozzle

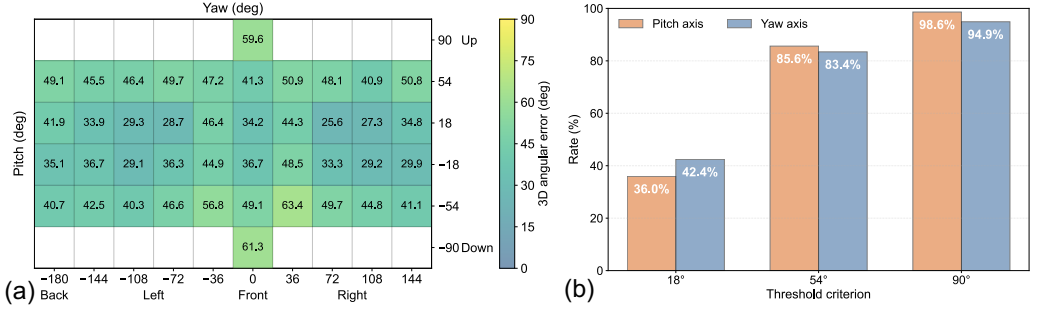


Fig. 8. (a) Heatmap of mean 3D angular error (deg) for each given direction under the 36° division; numbers indicate cell-wise means. (b) Within-threshold recognition rates on the pitch and yaw axes for three criteria: 18° (half-step), 54° (target division + one adjacent division), and 90° (target division + two adjacent divisions).

installations or rotating mechanisms. We defined target wind directions in spherical coordinates using pitch and yaw. Pitch was divided from -90° to 90° and yaw from -180° to 180° in 36° intervals, resulting in 42 target 3D directions after excluding yaw values at pitch = $\pm 90^\circ$. All target directions were rendered using our Airflow Rendering Algorithm, which computes nozzle activation patterns to approximate the desired head-centered wind direction.

Participants & Procedure. 24 participants (15 male, 9 female) were recruited for this study, aged 21–29 years ($M=24.1$, $SD=1.06$). We used the same calibration procedure as described in Section 4.1.2. The Direction Recognition Test followed the same structure as in Study 1 (Section 4.2.1), except that each participant completed 84 trials (42 target directions $\times$ 2 duration levels) presented in randomized order. The test lasted approximately 15 minutes, with a 1-minute break halfway through.

4.3.2 Results. Following the same analysis as in Study 1, we computed the 3D angular error between the perceived direction (derived from participants' head rotation) and the ground-truth direction for each trial, and reported this value as the 3D angular error for each trial. 36° directional sampling. A paired Wilcoxon signed-rank test on each participant's mean angular error showed no reliable difference between 2 s and 3 s ($Z = -0.357$, $p = 0.726$). Based on this result, we combined trials from both durations in the remaining analyses to obtain more stable estimates of direction-dependent error patterns.

Figure 8a visualizes the 3D angular error across the 42 target directions under the 36° grid. Recognition accuracy was not uniform over the pitch–yaw space: directions with moderate pitch angles (around $\pm 18^\circ$) generally yielded lower errors, whereas directions near the vertical extremes ($\pm 90^\circ$) showed substantially higher errors (around 60°). In addition, we observed larger errors for several directions in the downward-front region (e.g., pitch = -54° with yaw near $\pm 36^\circ$), suggesting that local airflow perception becomes less stable when the target direction contains a strong downward component. Overall, this pattern indicates that AirHook supports more reliable localization for directions near the horizontal plane than for steep vertical directions, which is consistent with the compact ear-worn geometry and non-uniform sensitivity around the ear.

To quantify practical localization precision under this denser sampling grid, we further computed within-threshold rates based on pitch and yaw angular errors between the perceived and given directions (Figure 8b). Using a strict half-step threshold of 18° (half of the 36° division), within-threshold rates were 36.0% on the pitch axis and 42.4% on the yaw axis. When relaxing the threshold to 54° , which covers the target division and one adjacent 36° division, within-threshold rates

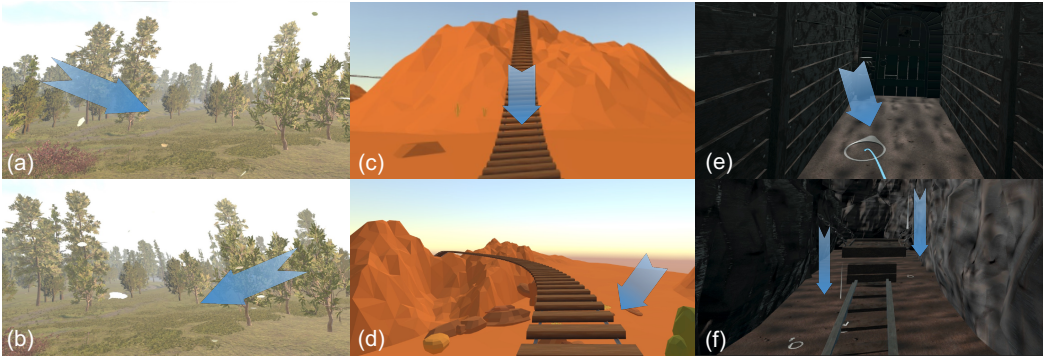


Fig. 9. Three Unity scenes used for evaluation. The Forest scene (a) when the ambient wind blows from the front-left, and (b) when the ambient wind blows from the front-right. The Rollercoaster scene (c) when climbing up, and (d) when turning left. The Mine scene (e) when using dash teleportation and (f) when walking through the dripping cave. The blue arrows represent the incoming wind direction in the VR scene's world frame.

increased to 85.6% for pitch and 83.4% for yaw. Together, these results suggest that while precise localization within a strict half-step criterion is challenging at a 36° sampling, participants can localize blended wind directions robustly within a slightly coarser neighborhood around the target direction—supporting our subsequent VR evaluation of whether multi-directional wind variation (vs. non-directional wind) yields measurable experiential benefits.

4.4 Study 3: Effect of Multi-directional Wind on VR Experience

We next examine whether AirHook's *multi-directional* wind cues yield measurable benefits in VR experience beyond the effect of simply "having wind" feedback. Building on Studies 1 and 2's perceptual characterization, Study 3 evaluates AirHook in ecologically grounded VR scenes and focuses on two experience outcomes—presence and enjoyment—under a within-subject design (3 scenes $\times$ 3 wind conditions; 9 trials per participant).

We designed three conditions to disentangle (i) the overall contribution of wind feedback and (ii) the additional contribution of wind directionality. In **No Wind**, participants experienced the scene without AirHook, providing a baseline VR experience without airflow cues. In **Non-directional Wind**, participants wore AirHook but received non-directional airflow (all nozzles activated with equalized intensity), controlling for the presence of airflow, device wear, and residual acoustic cues while removing directional information. In **Multi-directional Wind**, AirHook rendered directional airflow using our Airflow Rendering Algorithm, preserving both intensity and scene timing while adding directional correspondence between virtual wind events and perceived airflow direction. Across conditions, the visual and auditory scene content was held constant. To mitigate order effects, we counterbalanced nine trials using a Latin square (scene $\times$ wind-condition combinations).

4.4.1 Scenes. We implemented three Unity scenes¹ (Fig. 9), each containing scripted wind events triggered by different sources. Because wind in VR commonly arises from (a): environmental phenomena and (b) self-motion, we constructed **Environment-only**, **Motion-only**, and **Environment + Motion** scenes accordingly. To reduce behavioral variance, the first two scenes positioned participants as passive observers, allowing event timing and viewpoint changes to be tightly controlled. The third scene introduced active locomotion and controller-based interactions;

¹Available at: <https://github.com/KEIO-LCLAB/AirHook-VR>

however, navigation followed a fixed path, and the interaction sequence was prescribed to align event timing across participants and avoid confounding presence/enjoyment with individual play styles. Finally, to investigate experience under a longer exposure while minimizing motion-sickness risk, we assigned the longest duration to the Environment-only scene, where exposure time is fully controllable. Each scene included event-congruent audio effects synchronized with scripted scene events to support multimodal coherence (e.g., leaf rustling, rollercoaster track rumble, and dripping-water sounds).

Environment-only scene: Forest (3 minutes). Participants experience a sustained, gentle wind that gradually builds up from the world-forward direction. The wind direction slowly shifts from front to front-right, then to front-left, and finally returns to world-forward before fading out. Next, three brief, high-intensity gusts arrive from the world-back direction, each rapidly sweeping forward and stopping abruptly. As the wind blows, fallen leaves travel along its direction and trees sway accordingly. The wind uses the same visual mapping, in which the number and speed of falling leaves, as well as the amplitude of tree sway, scale proportionally with the intensity of the wind zone.

Motion-only scene: Rollercoaster (1 minute). The second scene takes the participants to a low-poly desert environment, seated in a mine cart on a wooden track. The rollercoaster sequence begins with a slow climb, followed by a short, steep 45° drop. The track then enters a horizontal left turn and proceeds into a long, steep 30° drop. It makes a small left turn again and finally decelerates forward to the end of the ride.

Environment + Motion scene: Mine (2 minutes). The third scene starts in an underground mine with a subtle ambient wind presented continuously. Participants advance through the mine using dash teleportation. At a T-junction, a rockfall collapses and blocks the forward path, forcing them to turn left into the side passage. Participants descend a short set of steps and enter a wide tunnel. Next, they pass through a narrow path where the wind intensifies, and exit into a wide tunnel. Participants press a lever to open the door ahead. Afterwards, they walk up the steps and enter a cave where water drips from the ceiling, which turns right to a wooden elevator suspended by chains. Upon the participants stepping onto the platform, the elevator ascends at a constant speed to ground level and delivers the participants to a lawn surrounded by mountains, where the scene concludes.

4.4.2 Participants & Procedure. The same group of participants in Study 2 (Section 4.3.1) participated in this session. They reported their previous experience with VR on a five-point Likert scale (1 = no experience, 5 = very experienced) with an average score of 2.00 (SD = 1.06). None of the participants exhibited motion sickness throughout the study.

Participants first completed the same calibration procedure as in Studies 1 & 2. At the start of each trial, participants put on a Meta Quest 3 headset with the help of the researcher and wore AirPods Pro with noise-canceling function turned on. Participants wore the correctly sized AirHook only in the Non-directional Wind and Multi-directional Wind conditions. Participants were given a handheld controller and asked to stand up if the trial involved the Mine scene. Then, participants experienced the assigned VR scene under the designated wind condition. Upon completing the scene, participants took off the headset and filled out a Presence and Enjoyment questionnaire for every trial until the procedure was completed. Referring to the evaluation on the VaiR system [54], we used the E²I questionnaire [42] to assess the participants' presence and enjoyment score, excluding items on the memory task, comparison between VR scenes, and willingness to pay due to irrelevance. After completing the questionnaire, participants proceeded to the next trial. The nine trials took approximately 60 minutes in total. Following all trials, we conducted a semi-structured

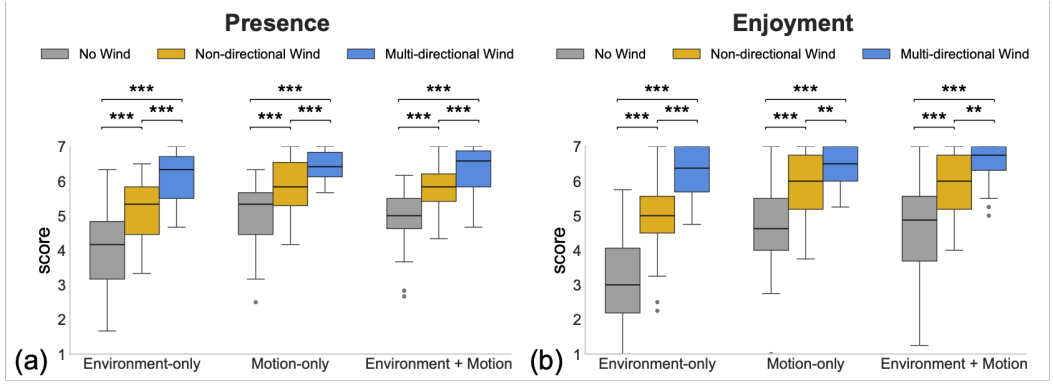


Fig. 10. The result of E²I questionnaire on a 7-point Likert scale: (a) Presence Score; (b) Enjoyment score. Significance: ** $p < .01$, *** $p < .001$.

interview to capture qualitative differences in perceived wind realism, scene congruence, and any distraction or discomfort associated with wearing AirHook.

4.4.3 Quantitative Results.

10 questions from the E²I questionnaire were used to assess participants' VR experience after each trial (7-point Likert). We computed two composite scores: *presence* as the mean of six items spanning sensory, distraction (reverse-scored), realism, and control factors, and *enjoyment* as the mean of the remaining four items capturing pleasure and satisfaction. Figure 10 summarizes the results across the three scenes and wind conditions. To test for condition effects in our within-subject design, we applied Friedman tests followed by Holm-corrected Wilcoxon signed-rank tests [15]. Importantly, the post-hoc comparisons were planned to disentangle (i) the overall benefit of adding wind feedback (Non-directional/Multi-directional vs. No Wind) and (ii) the additional benefit of wind directionality (Multi-directional vs. Non-directional).

For **presence**, wind condition had a significant overall effect ($\chi^2(2) = 45.537$, $p < .001$ ***). Holm-corrected post-hoc tests showed that introducing wind via AirHook increased presence relative to No Wind in both the Non-directional condition ($Z = -4.197$, $p_{\text{Holm}} < .001$ ***) and the Multi-directional condition ($Z = -4.286$, $p_{\text{Holm}} < .001$ ***). Crucially, Multi-directional Wind further increased presence compared to Non-directional Wind ($Z = -4.143$, $p_{\text{Holm}} < .001$ ***), indicating that the gain is not solely attributable to “having wind” but also to providing *directionally structured* airflow that is more consistent with the virtual scene. Figure 10a reports per-scene presence scores, and the significance markers indicate Holm-corrected pairwise comparisons that meet the same significance criterion across all scenes ($p_{\text{Holm}} < .001$ ***). Because AirHook operates near the ears, we additionally examined the distraction factor item(s) related to external interruptions (e.g., noises). We found no significant change in distraction across conditions (Friedman + Holm-corrected Wilcoxon), suggesting that the observed presence improvements are unlikely to be explained by increased perceived distraction due to device noise.

For **enjoyment**, wind condition also showed a significant overall effect ($\chi^2(2) = 44.333$, $p < .001$ ***). Post-hoc tests mirrored the presence results: both Non-directional Wind ($Z = -4.286$, $p_{\text{Holm}} < .001$ ***) and Multi-directional Wind ($Z = -4.286$, $p_{\text{Holm}} < 0.001$ ***) were rated as more enjoyable than No Wind, and Multi-directional Wind was significantly more enjoyable than Non-directional Wind ($Z = -4.143$, $p_{\text{Holm}} < .001$ ***). This pattern supports the interpretation that multi-directional airflow can enhance enjoyment in VR, while adding directional structure yields an

additional benefit beyond non-directional wind. Figure 10b shows enjoyment scores per scene; all planned post-hoc comparisons met the same significance threshold across scenes ($p_{\text{Holm}} < .001^{***}$), except that the Multi-directional Wind vs. Non-directional Wind comparison was weaker in the Motion-only and Environment + Motion scenes ($p_{\text{Holm}} < .01^{**}$). This scene-dependent weakening suggests a potential boundary condition: when self-motion cues already dominate the experience, the incremental benefit of directional wind may be reduced, a point we further unpack through qualitative responses in the next section.

4.4.4 Qualitative Results. We conducted an inductive thematic analysis of the interview transcripts. Two researchers independently open-coded the interview transcripts at the level of meaningful excerpts (sentences/turns), then consolidated codes into a shared document through discussion. We iteratively clustered codes into higher-order themes using affinity diagramming, resolving disagreements via discussion (and a third author when needed). Themes stabilized in later transcripts, with no substantially new themes emerging. Based on this analysis, we summarized participants' feedback along three recurring themes: (1) Directional Wind for Presence: Spatial Attribution and Head-Turn Coherence; (2) Wind as a Cue: Events and State Changes; (3) Usability and Wearing Comfort.

Theme 1: Directional Wind for Presence: Spatial Attribution and Head-Turn Coherence.

Participants frequently described wind provided by AirHook not merely as a background effect, but as an *informative* cue that helped them interpret where events were coming from and what the environment was "doing". Participants reported that the experience without wind "*felt like watching a video*" (P9, P17), and was "*hard to stay focused*" (P14). In contrast, directional wind helped participants "*feel where the wind comes from without intentionally tracking the drifting leaves*" (P11), making the scene feel more grounded and interpretable.

A key mechanism underlying this presence benefit was *spatiotemporal coherence* between airflow direction and head orientation. Participants emphasized that directional wind "*remained meaningful even when turning the head*" (P10, P21), as the perceived direction stayed consistent with the scene, allowing them to attribute the airflow to a virtual source rather than to the device. In contrast, non-directional wind felt detached from the virtual world because it created "*a sense of mismatch when the wind stayed the same as the head turned or as the leaves changed direction*" (P12).

Some participants described the directional wind as strongly evoking curiosity and prompting exploration by providing a responsive dimension that users can actively probe: "*wanting to see what would happen if I faced different directions*" (P5, P13, P17), or "*wondering 'maybe something is over here,' and starting to look and find things*" (P9). Directional wind also appeared to sustain affective engagement over time, as one participant noted that "*time seemed to pass fastest with multi-directional wind, and slowest with no wind*" (P10).

Overall, these comments illustrate the contribution of wind directionality and head-turn coherence in strengthening presence and encouraging active engagement with the surrounding scene.

Theme 2: Wind as a Cue: Events and State Changes.

Environmental Events. Participants suggested that wind appeared to function as an event cue that helped them localize where something happened and attribute meaning to it (e.g., danger). When wind accompanied the automatically triggered events (e.g., rock collapse), several participants reported being "*more surprised and immersed*" (P2, P6) and experiencing it as "*a complete event that includes seeing the rocks falling, hearing the sound, and feeling the wind*" (P3). Others emphasized that the wind conveyed where the event originated in the surrounding space, for example: "*The*

wind reached me and told me that something had fallen somewhere out of reach.” (P5), and “The wind made me feel the way was blocked, so I could only go another way without thinking about it.” (P16).

Additionally, participants highlighted the airflow less as “wind” and more as a cue that helped them interpret the simulated phenomenon. They noted that brief wind impacts near the ear created “a cool sensation” (P12, P22) and “a feeling of ears getting wet” (P1), which supported an impression of dripping water.

Together, these reflections indicate that AirHook can deliver localized airflow that moves beyond a generic wind sensation and function as an embodied cue for environmental events.

Motion and Transitions. Participants indicated that the wind demonstrated changes in spatial layout and openness. For example, participants described the narrow passage as feeling “like the path was enclosing me” (P5), and noted that “this sensation disappeared upon exiting into a wider space, which made the spatial difference feel stronger” (P5, P19). This shift also strengthened participants’ sense of participation by making the environment feel spatially situated around them; as one participant remarked, “I could feel the terrain around me and my position relative to it” (P17).

Participants further described directional wind as a kinematic sensation that sharpened the sense of self-motion in VR. In the Rollercoaster scene, participants reported “feeling like I was moving” (P9, P10, P19), and downhill segments were perceived as “going faster” (P2, P12, P22). This effect was reinforced when the sense of wind “matched intuition” (P7). Some participants further reported intensified motion-related sensations through the wind, such as “weightlessness” during downhill (P8, P18, P19) and “centrifugal force” during turns (P5, P8, P12). However, some participants framed the rollercoaster as inherently engaging (P2, P10) and viewed the absence of directionality as “acceptable under fast motion” (P4, P19). Such tolerance was also supported by real-world expectations that “at that speed I suppose that wind hits me broadly” (P20). This is consistent with quantitative results in Section 4.4.3: when self-motion cues are already salient, directionality may be less diagnostic and offer smaller incremental gains.

Our system also supported interaction-triggered transitions by making brief movement events register as tangible kinematic changes, for example: “teleportation initially felt unlike real walking and a bit odd, but the wind accompanying the movement helped me understand how I was moving” (P15). This suggests that airflow made the transition feel less like an abrupt scene update and more like a physically experienced movement, also described as “a feeling of being pushed forward” (P11, P16) or “jumping” (P24). Similarly, participants reported a strong impression of vertical motion in the elevator, including the feeling of “cutting through the air as moving upward” (P5).

Overall, these comments position wind as a kinematic marker of state and transition—supporting both self-initiated and system-driven movement as something users can physically track.

Theme 3: Usability and Wearing Comfort. Participants generally noted AirHook as low-burden to wear in VR. Our system was characterized as “light” and non-intrusive, as “the weight is offloaded elsewhere rather than onto the user.” (P3). This perception was echoed by others, who noted that “not really feel like I was wearing something” (P5, P9, P19, P20). These comments indicate that distributing actuation weight away from the head can preserve wearing comfort while helping users stay focused on the VR experience rather than on the device itself.

Several participants noted that such comfort is context-dependent: when worn alongside an HMD, AirHook’s relatively low physical presence tends to fade into the background and “creates almost no extra burden” (P7). Immersion in the VR content further reduces awareness of wearing it because “the impression of the wind coming was stronger.” (P10). This suggests that perceived burden is not only a matter of physical mass, but also of how the device competes for attention relative to the VR apparatus and ongoing tasks, which participants described as being largely minimized in our system.

Additionally, the wearing interaction was described as “*intuitive and easy to understand as the structure is basically just ‘wear it’*” (P10), suggesting that ear-worn wind displays can minimize the need for elaborate donning adjustments. This intuitiveness was often grounded in familiar wearing metaphors such as “*glasses*” (P1, P16) and “*hook-style earphones*” (P16, P23). Participants also suggested that using AirHook involved a short learning curve and became low-effort thereafter; for example, “*Once I knew how to put it on, I could do it quickly, almost without thinking*” (P19).

Overall, AirHook is framed as a practical ear-worn add-on for VR, imposing minimal wearing demand in use and remaining easy to adopt through a straightforward donning routine.

5 Discussion

5.1 Design Targets for Ear-centered Multi-directional Wind Rendering

A core question for ear-centered airflow displays is what level of temporal and directional fidelity is practically necessary for wind cues to remain interpretable in VR. We provide two complementary constraints from Study 1 (Section 4.2) and Study 2 (Section 4.3).

First, **stimulus duration is not the primary determinant** of directional perception. Across 1–10 s exposures, recognition remained broadly stable, while the shortest tested duration (1 s) was more likely to yield unstable perception. This suggests that, for interactive VR events (e.g., gusts, pass-bys, brief prompts), designers can prioritize responsiveness and reduced disruption without assuming that longer playback is required for direction recognition.

Instead, the more important factor is delivering a steady, perceptually “settled” airflow during the cue window. In the VR evaluation (Section 4.4.3), momentary wind cues accompanying brief events such as teleportation and rock collapse, were perceived as tactile changes in the virtual environment. Particularly for teleportation, prior work has demonstrated distance-dependent control of airflow duration [59]; complementing this approach, an instantaneous burst of wind can also support users’ understanding and perception of teleportation as a jump-like movement. These observations suggest that airflow can be choreographed not only around sustained environmental or motion effects, but also around ephemeral scene events and user actions.

Second, with sufficiently steady wind delivery, participants could recognize **coarse 3D directional cues under a 36° division** at a reliable, but not-angle-accurate level. Crucially, this indicates that users can distinguish a set of spatial directions that extends beyond the device’s discrete nozzle orientations, even with a fixed nozzle layout. To achieve such directional resolution, prior head-mounted systems have commonly arranged airflow sources around the head at a comparable spatial density, such as the eight fans in Head Mounted Wind [7] or the ten nozzles mounted on rotatable bows in VaiR [54]. In contrast, AirHook reduces reliance on one-to-one mappings between outlet positions and perceived directions while reducing the physical coverage of airflow from the area around the head to the ears. These findings reposition the design goal for ear-based wind feedback: rather than chasing angle-level readout, a practical target is to support coarse 3D direction categories that remain stable under head movement—thereby preserving a lightweight, non-actuated form factor while still enabling meaningful spatial variation.

For ear-worn multi-directional wind, the “right” target is often *category-level 3D directionality plus temporal stability*, not fine angular accuracy. This framing is useful for both hardware design (fixed nozzles can be sufficient) and rendering algorithms (focus on stable directional bins, smoothing, and latency control).

5.2 Spatial Wind as a Coherent Environmental Cue

Real-Time cross-modal coherence as the key mechanism. Multi-directional wind can strengthen cross-modal coherence by providing directional information aligned with the audiovisual cues in real time. Because airflow is registered through direct skin contact, participants described it as something they could feel without needing to visually verify subtle scene cues. This extends the role of airflow from a supplementary effect to an active component of multisensory integration. It supports a more comprehensive understanding of the virtual situation, consistent with AirWhisper’s account of airflow as part of combined sensory evidence [66].

Directional wind as an interactional and expressive channel. The coherent display of multi-directional wind appears to influence not only participants’ subjective evaluations of the overall experience but also the behavioral strategies they adopt during engagement. Although the improvement from *No Wind* to *Non-directional Wind* already supports VaiR’s assumption regarding airflow’s impact in interactive gaming settings [54], multi-directional wind adds another layer by encouraging user exploration of the virtual environment as it more actively responds to their actions.

Even within VR scenarios with limited, pre-defined airflow variations, users can elicit new directional wind sensations by simply changing their own orientation (e.g., turning their head or body), owing to our dynamic calculation of airflow in a head-centered reference frame. Once users develop an understanding of the system’s responsiveness, it can spark curiosity and prompt them to look around, probe the directionality of the wind, and hence remain actively engaged. Therefore, multi-directional wind can serve as an expressive augmentation to VR experiences beyond signaling the presence of wind.

Different functional roles across scene types. HMD-based VR experiences often involve diverse scene types, where a single “multi-directional wind” implementation is not necessarily optimal across contexts. Prior work has evaluated their airflow systems in specific VR genres, such as passive-viewing experiences in VaIR [54] or locomotion-oriented scenarios in AirWhisper [66], leaving how directional airflow should be configured across interactive scenarios as an open question. For example, wind can emerge from different sources and vary through higher-dimensional dynamics. Participant feedback in the evaluation of AirHook reflects a clear distinction between scenes with different genres: **environment-driven wind** (e.g., weather, ambient flows) tends to shape atmosphere and emotional tone by making environmental dynamics perceptible; **motion-driven wind** (e.g., self-motion, inertia cues) more directly reinforces kinematic structure and phantom sensations of momentum. Our study expands the configuration space of multi-directional wind, suggesting that designers could align directional wind behaviors with the intended experiential goal: in *environment-centric moments*, multi-directional wind can foreground spatial attribution and environmental change; in *motion-centric moments*, it can reinforce self-motion cues and continuity of movement.

6 Limitations

Deployment constraint. Compared with fully integrated devices, our current configuration offloads the pneumatic supply to an external unit, reducing the on-head wearing burden but increases the deployment footprint and may constrain mobility in untethered scenarios. This constraint reflects an engineering trade-off between a compact display and the demands of airflow actuation, motivating future work on tighter integration (e.g., miniaturized actuation and power delivery) to enable more seamless everyday deployment. While this form factor does not affect the core

rendering pipeline evaluated in our studies, it may influence ecological usability in longer and more mobile VR sessions.

This external actuation configuration also introduces latency, including motor response time and the airflow transmission through the pipes. In our evaluation, this latency is most relevant to Study 3 (Section 4.4), where wind feedback was triggered by interactive VR events. Because these scenes involved user-driven behavior rather than fully preprogrammed sequences, the system could not simply compensate for latency by scheduling wind cues in advance. Nevertheless, participants did not report noticeable delay or temporal mismatch in the interviews, suggesting that the current system latency (approximately 112.5 ms as reported in Section 3.4) was within an acceptable range for the interactive wind feedback used. We do not claim this as a general perceptual threshold: more time-critical applications or faster motion events may require lower latency, and further reducing actuation delay remains an important direction for improving responsiveness and multisensory coherence.

Comparison with prior wind interfaces for VR. A natural question is how AirHook compares to prior wind interfaces for VR (e.g., fan-based, or alternative wearable airflow systems) [37, 54]. We did not conduct a head-to-head benchmark against existing devices. Such comparisons are non-trivial to make fair and reproducible in HCI systems work: wind displays differ in physical placement (room-scale vs wearable), airflow field geometry, latency, operating noise, and coupling with head motion, and replicating prior systems often requires bespoke hardware and calibration procedures that are not readily accessible. Moreover, unlike standard perception tasks where accuracy metrics are directly comparable across implementations, the experiential outcomes we study (presence and enjoyment) are sensitive to scene design, event timing, and device form factor, making cross-device comparisons difficult to interpret without a shared experimental pipeline. To mitigate this limitation, we anchored our evaluation in two complementary ways: (1) we adopted a directional sampling benchmark (36° grid) used in prior work [54] to contextualize perceptual resolution, and (2) we employed an ablation-style within-device comparison (No Wind vs. Non-directional Wind vs. Multi-directional Wind) to isolate the incremental contribution of wind directionality while controlling for device wear, airflow sensation, and residual acoustic cues. Future work could pursue broader comparisons by standardizing a set of open scenes and wind-event scripts, and evaluating multiple devices under an identical authoring and calibration protocol.

User study scope and individual differences. AirHook relies on an ear-worn form factor, and user-specific factors—such as ear geometry, skin exposure around the pinna (e.g., hair coverage), device fit, and tactile sensitivity to airflow—may contribute to variability in both perceived direction and wearing experience. In our studies, 8 of 24 participants completed the experiments while wearing glasses, and we did not receive complaints indicating that glasses interfered with AirHook use. Nevertheless, eyewear compatibility remains an important practical consideration. Future designs could further reduce interference with glasses through refined off-ear loading and alternative nozzle placement, such as recessing the upper ear-hook region where it overlaps with the glasses arm or moving the front-up nozzles downward to leave clearance for the glasses arm.

While our calibration procedure (Section 4.1.2) aims to reduce intensity confounds across nozzles, it also introduces setup overhead; future work could explore faster or implicit calibration approaches and validate robustness under natural variations in fit and occlusion. Our study also used a partially overlapping multi-session participant structure, as described in Section 4.1.1. Repeated-measures designs are common in HCI because they help control participant-level variability, but they require attention to learning and carryover effects [5]. Although fully separating participant pools across studies would provide cleaner isolation, we used partially overlapping samples to control individual differences and maintain consistency in participants' perceptual baselines. While carryover cannot

be completely ruled out, this risk was mitigated by the design of the studies: all sessions were separated by at least one day, and participants received no trial-by-trial feedback during the direction-recognition tasks in Studies 1 and 2. Moreover, the primary comparisons in Study 3 were made within the VR study itself (No Wind vs. Non-directional Wind vs. Multi-directional Wind), rather than relying on comparisons against performance in Studies 1 or 2. Larger and more diverse samples would allow future work to estimate effect sizes more precisely, test scene $\times$ wind condition interactions with higher statistical power, and better characterize how individual fit and sensitivity shape ear-based wind perception.

Evaluation duration and VR scene fidelity. The developed VR scenes were controlled to a brief evaluation period (1–3 minutes), leaving AirHook’s sustained usability and participants’ habituation to wind stimuli insufficiently investigated. More complete interaction loops in future VR systems could better separate initial novelty effects from sustained effects. The lack of audiovisual details in current VR scenes may influence how wind feedback contributes to multi-sensory coherence and participants’ perceptual understanding of the virtual environment. Evaluations in more polished and content-rich VR scenarios could assess longer-term effects and broaden ecological validity. In addition, our evaluation primarily relied on self-report measures; future studies could triangulate experience outcomes with behavioral proxies (e.g., head turns, exploration time) and physiological measures where appropriate.

7 Conclusion

This paper presented AirHook, an ear-worn airflow interface that renders multi-directional wind cues around the ear for VR while maintaining a lightweight, non-obtrusive form factor. Through three user studies, we first characterized users’ 3D directional perception with AirHook, showing stable recognition across typical stimulus durations and reliable coarse-grained 3D direction recognition at a 36° benchmark, supporting intermediate directions beyond the discrete nozzle layout. We then evaluated AirHook in ecologically grounded VR scenes and showed that multi-directional wind provides additional experiential value beyond non-directional wind, improving presence and enjoyment while revealing how real-time cross-modal coherence under head movement underpins these gains. These findings motivate future ear-worn wind displays that support interpretable directional cues while remaining lightweight, responsive, and adaptable to diverse VR experiences and interaction contexts.

Acknowledgments

This work was partially supported by JST Keio-SPRING (Grant Number Y01GQ25163, Y01GQ26205), and JST AIP Acceleration Research (Grant Number JPMJCR25U4).

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