Journal on Interactive Systems, 2025, 16:1, doi: 10.5753/jis.2025.5955

Prototyping and Evaluating TWIRL: A Temperature-Controlled DIY Airflow System for Enhancing Immersive Media

Aleph Campos da Silveira [**Federal University of Espirito Santo** | ***alephcampos@gmail.com***]
Eduardo Correa Rodrigues [**Federal University of Espirito Santo** | ***eduardo.rodrigues@edu.ufes.br***]
Estevao Bissoli Saleme [**Federal University of Espirito Santo** | ***estevao.saleme@edu.ufes.br***]
Alexandra Covaci [**University of Kent** | ***a.Covaci@kent.ac.uk***]
Gheorghita Ghinea [**Brunel University London** | ***george.ghinea@brunel.ac.uk***]
Celso Alberto Saibel Santos [**Federal University of Espirito Santo** | ***saibel@inf.ufes.br***]

Department of Informatics, Federal University of Espírito Santo (UFES), Av. Fernando Ferrari, 514, Goiabeiras, Vitória, ES, 29075-910, Brazil

Received: 23 April 2025 • **Accepted:** 15 August 2025 • **Published:** 24 September 2025

Abstract: This study presents the design, prototyping, and user-centered evaluation of TWIRL (Thermal Wind Right and Left), a low-cost, temperature-controlled airflow system aimed at enhancing immersion in multisensory media experiences. TWIRL integrates hot and cold airflow generation, via Peltier-based cooling modules and modified hairdryer heating units, synchronized with audiovisual content using Sensory Effects Metadata (MPEG-V). A preliminary user study (N = 12) evaluated perceived realism, enjoyment, comfort, and engagement while experiencing thermally congruent video stimuli. The results indicated high participant acceptance, with thermal effects classified as realistic, pleasant, and nonintrusive, supported by strong internal consistency metrics. The participants expressed a willingness to use TWIRL in the future and recommend it, suggesting the potential of TWIRL to increase the presence and enjoyment of multisensory systems. The findings contribute to the understanding of thermal-wind integration in mulsemedia and offer design guidelines for future scalable, multisensory systems in the entertainment, education, and accessibility domains.

Keywords: Haptics, Multisensory experiences, Thermal stimuli, Wind, Airflow

1 Introduction

One of the motivations behind the appeal and fascination with media is its ability to create reproductions of reality, allowing users to be transported to other lands. Experiences with non-interactive and interactive media depicting simulated realities are characterized by direct perceptual stimulation and the presence of "being there" resulting from the interplay of raw multisensory data and complex cognitive processes [IJsselsteijn and Riva, 2003].

By offering the possibility to engineer a better user experience, presence has become a common term in advanced media such as broadcast or Virtual Reality (VR). Although existing research focuses on visual and aural senses as primary modalities to engender a sense of presence in participants, increasing the breadth and depth of sensory experiences and transitioning to multisensory applications have been shown to improve the experience of user media [Han *et al.*, 2024; IJsselsteijn and Riva, 2003; Covaci *et al.*, 2019; Wilberz *et al.*, 2020; Chen *et al.*, 2024; Hosoi *et al.*, 2023].

This paper extends the technical work of Rodrigues *et al.* [2021] and the airflow performance evaluation by Saleme *et al.* [2023], both of which focused on hardware design, thermal control, and physical deployment of TWIRL (Thermal Wind Right and Left), a DIY temperature-controlled airflow system. In contrast to previous studies, the present research prioritizes a user-centered evaluation, emphasizing subjective measures such as perceived user experience, enjoyment, comfort, and overall impressions of thermal wind effects when synchronized with audiovisual content. By shifting the focus from system-level feasibility analyses to the assessment of participant perception, this study offers novel insights into how mulsemedia systems are experienced, interpreted, and valued by end users.

The two studies mentioned in the preceding paragraph have analyzed the experimental setup design and illuminated the possibilities and limitations of working with airflows at varying temperatures. In this paper, we build on those studies by conducting a user evaluation to assess participants' perceptions and experiences with TWIRL. This evaluation provides valuable information on the strengths and limitations of the device, particularly regarding the intensity of the effects of cold and hot wind, the level of enjoyment, and the overall user experience.

Following this brief introduction, the remainder of the text is organized as follows. Section 2 presents related work. Then, Section 3 presents the TWIRL system and its devices. Section 4 describes the design of the experiments and our user evaluation, followed by Section 5, which discusses the implications, limitations, and future directions, highlighting insightful conclusions.

2 Related Work

This section reviews previous work related to our proposal, focusing on systems that generate cold and hot airflows to enhance multisensory user experiences. Although Section 1 introduced the broader motivation for mulsemedia research, here we emphasize recent technological developments and highlight key approaches that inform the design and evaluation of the TWIRL system.

da Silveira *et al.* [2023] presented an extensive review of devices capable of emitting thermal wind to enhance multisensory human-computer interaction. The authors discuss various technologies integrating airflow and temperature control to create tactile sensations, emphasizing how combining hot and cold air streams can produce distinct sensory experiences. The conclusion emphasizes the potential of these devices for applications in immersive environments, highlighting the importance of synchronizing thermal changes with visual and auditory cues for realistic experiences.

Hosoi *et al.* [2023] proposed a novel method to induce wind perception without airflow. Using cross-modal cues, including visual, auditory, vibrotactile, and thermal stimuli, the study demonstrates how users can experience the sensation of wind without direct physical wind contact. The findings suggest integrating multiple sensory channels can significantly enhance the illusion of wind, providing new opportunities for haptic interface design. The conclusion underscores the effectiveness of cross-modal interactions in simulating environmental sensations realistically.

Singhal *et al.* [2023] introduced a cutting-edge display system that combines ultrasonic haptics with heat modules to produce tactile and thermal feedback in the air. This system allows users to feel temperature changes without physical contact with devices, offering a new way to experience haptic feedback in AR/VR settings. The authors conclude that integrating thermal feedback into mid-air haptics significantly enhances the immersion and realism of interactive applications, especially in scenarios where touch is not feasible.

Xu *et al.* [2023] proposed a discussion about how to mimic cold sensations without reducing skin temperature. Their system creates an illusion of coldness while maintaining a stable skin temperature by combining cool airflow and specific light wavelengths. The authors found that the perception of cold is more influenced by airflow patterns and lighting cues than by actual temperature changes. The conclusion points to practical applications in VR and interactive installations where real-time cooling may be impractical or uncomfortable.

Zhao *et al.* [2024] introduced AirWhisper, a modular wearable device that generates dynamic multidirectional airflow around the user's head using four micro fans and 3D printed attachments. The authors conducted a Just Noticeable Difference (JND) study to optimize airflow perception and a series of experiments demonstrating that combining visual and airflow feedback significantly enhances realism and user engagement in VR. Their work highlights the potential of adaptive multimodal models centered on humans that dynamically adjust outputs based on real-time user perception and environmental context. Scenarios with varying airflow patterns and interaction levels further validated the system's versatility, underscoring the importance of personalized haptic feedback in immersive environments.

Lastly, Chen *et al.* [2024] proposed FlowZen, a hybrid haptic system combining stationary non-contact devices with handheld contact-based actuators to bridge these limitations. Their approach leverages particle-based visual effects to unify tactile illusions (e.g., wind, heat) across devices, synchronizing localized haptic feedback from handheld controllers with full-body airflow/thermal cues from stationary units. The experimental results demonstrated enhanced spatial coherence and user immersion, with the hybrid design enabling adaptive feedback that adjusts to the user's movement and the environmental context. This work underscores the potential of multimodal integration to overcome trade-offs between stationary and portable haptic systems.

Numerous attempts have been made to simulate wind effects in multimedia and VR systems. Typically, these systems use static fans or portable devices to generate airflow [Cardin *et al.*, 2007; Ranasinghe *et al.*, 2017, 2018; Covaci *et al.*, 2019; Peiris *et al.*, 2017]. However, most implementations lack adequate temperature control, which limits their ability to deliver a realistic multisensory experience.

Among the few systems that incorporate both wind and thermal feedback, Ambiotherm [Ranasinghe *et al.*, 2017] and Season Traveller [Ranasinghe *et al.*, 2018] stand out. However, these systems utilize separate sources for wind and temperature effects, which can result in potential incoherence between sensory stimuli. In contrast, Suzuki and Matsuura [2019] and Ogiwara *et al.* [2020] have proposed a system designed to emit a hot wind directed at the user's face during a VR experience. Nevertheless, this approach has not been evaluated from the user's perspective and exclusively focuses on delivering hot air.

Furthermore, existing wind and temperature-based haptic systems generally lack integrated thermal components capable of generating cold and hot airflows, as noted by Sardo *et al.* [2018]. This disparity highlights the need for innovative solutions capable of seamlessly integrating wind and temperature feedback into immersive environments. Although these studies have advanced the state-of-the-art in simulating wind and thermal stimuli, most focus on technical implementations or specific device capabilities, often without user-centered evaluations. In contrast, our work differs by focusing on the end-user perspective through a structured user study. We examine how synchronized cold and hot airflow, when integrated with audiovisual media, influences subjective user experience, an aspect not comprehensively addressed in the works cited in this section.

3 TWIRL

TWIRL is a platform that simulates real-world conditions with hot/cold wind to enhance physical presence in mulsemedia. In line with the approach advocated by Saleme *et al.* [2019a], the TWIRL prototype, shown in Figure 1, can deliver temperature-controlled airflows synchronized with audiovisual content through cold and hot wind devices. It includes (1) a computer running a video player and a sensory effects renderer to process Sensory Effects Metadata (SEM) [Saleme *et al.*, 2019b] and manage presentation devices; (2) a custom cooling system integrated with Philips amBX devices for cold wind; and (3) hair dryers connected to a microcontroller for hot wind.

Figure 1. The TWIRL prototype consists of two pairs of cold (green) and hot wind (red) devices that can work with both a screen and a VR headset. The bottom right corner features a thermal image illustrating the devices in an operational state. Red means heat, whereas dark blue is coldness [Rodrigues *et al.*, 2021].

Cold Wind Device: To manage the complexity of the TWIRL device, a 3D model was implemented to visualize the configuration and integration of its components (Figure 2). At the heart of the device lies a Peltier Effect component that facilitates heat exchange between semiconductors by manipulating an electric current. In the TWIRL prototype, this element cools 125 ml of water in an aluminum container wrapped in Styrofoam and covered by a 3D-printed cover. An ultrasonic humidifier converts water into mist using a piezoelectric element. The mist is then extracted by a mini cooler and directed to the user via a Philips amBX fan. A heatsink and cooler at the bottom of the device remove heat and prevent interaction between the heated and cold sides of the Peltier element. A 12V 600W power supply energizes the Peltier element and dissipators. The humidifier and mini-coolers are operated by a relay module activated by an Arduino Uno.

The technical evaluations of Rodrigues *et al.* [2021] showed that the combined mist plus fan condition produced a steady decrease in air temperature, the cold subsystem produced an approximate temperature drop of ≈ 2 °C over 30 s, with observed minima of 25.5 °C (scenario 1) and 17.5 °C (scenario 2). The mean wind speed during cold tests was about 1.0 m/s and the average remaining water volume in the reservoir after testing was 118 mL.

Hot Wind Device: TWIRL's hot airflows are generated by two hairdryers, which have small fans and resistors to deliver two temperature levels (hot and very hot). The nominal power of each is 1200 W, configured to work at a quarter of this power, with a consequent reduction in maximum temperatures to avoid harm and damage in case of high temperatures. As illustrated in Figure 3, which shows one of TWIRL's hot wind devices. In this device, (1) a hairdryer is connected to a (2) relay module, which is controlled by a (3) Arduino Uno microcontroller.

The technical analysis conducted in Rodrigues *et al.* [2021] revealed that the warm air device resulted in an average temperature rise of nearly 10 °C within 30 s, with peak temperatures reaching 37 °C (scenario 1) and 30 °C (scenario 2). The mean wind speed for the hot tests was about 1.4 m/s. The stronger heating response is consistent with the actuator power difference in the prototype (hair dryers operating at

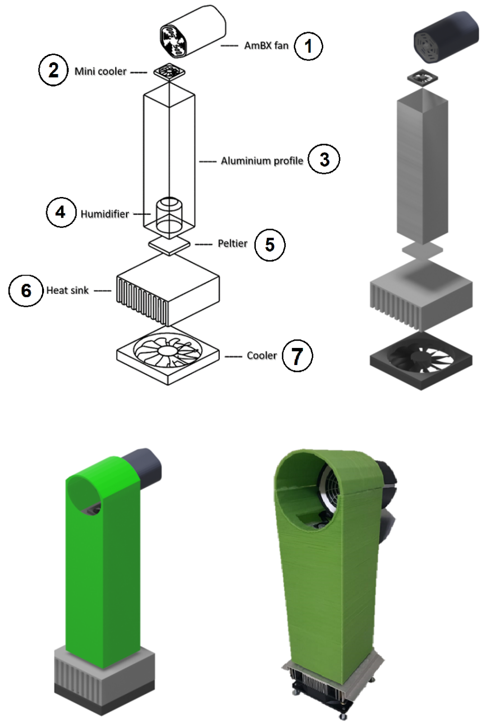

Figure 2. Cold wind device design (top) and its assembled structure (bottom) [Rodrigues *et al.*, 2021]. The components are the following: (1) Philips amBX fan, (2) Mini cooler, (3) Aluminium profile, (4) water container, (5) Peltier element, (7) Cooler to dissipate heat, (6) Heat sink.

approximately 300 W each versus Peltier elements rated at ≈144 W each). The measured temperature change rates were of the order of ≈ 4 °C/min for cooled flows and ≈ 20 °C/min for heated flows. Since a variation greater than 1 °C is typically perceptible, the observed amplitudes and rates are sufficient for users to detect thermal variations.

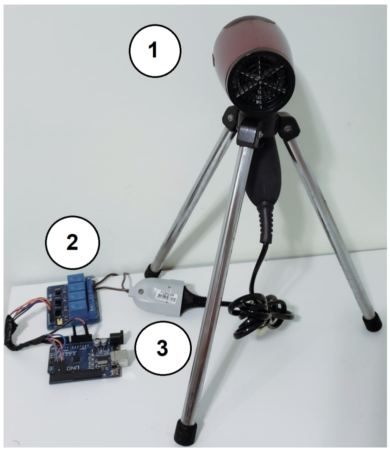

Figure 3. Hot wind device with the relay module (2) connected to an Arduino Uno (3) and one of the hairdryers (1) used in TWIRL.

Table 1 presents the estimated cost for each component of the system. It does not include the amBX system and its wind fans, which are no longer available commercially.

4 Methods and Experimental Design

The experiments used *PlaySEM Video Player* [Saleme and Santos, 2015] and *PlaySEM SER 2* [Saleme *et al.*, 2019b] to

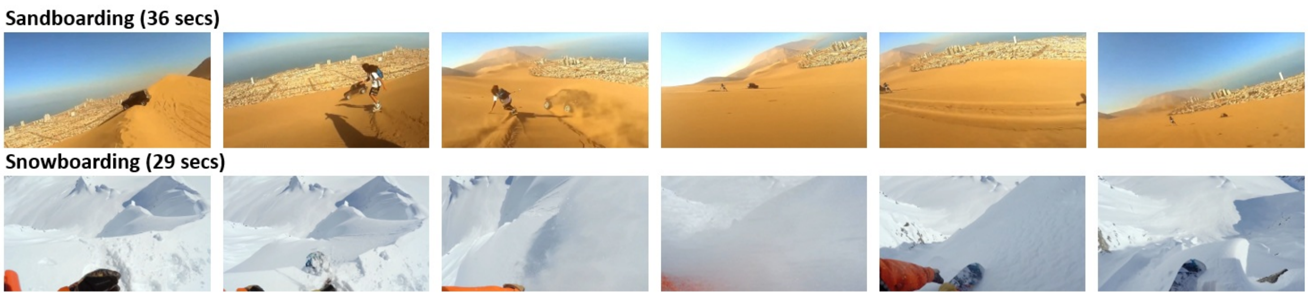

Figure 4. Snapshots from the videos used in the experimental evaluations. **Sandboarding** and **Snowboarding** are annotated, respectively, with warm cold airflows.

Table 1. Estimated cost of TWIRL's components at July 2025 prices

Type	Component	Objective	Unit cost (U$)	Quant.	Line total (U$)
Microcontroller	Arduino Uno R3	Controller	30	1	30
Electronic component	TEC1-12712 40×40 mm Thermoelectric Cooler (12 V)	Voltage-activated thermoelectric cooler/heater	6	2	12
Passive thermal comp.	Heatsink (dissipater)	Heat Dissipation	10	2	20
Electronic component	12 V fan	Heat Dissipation	12	2	24
Electronic component	Relay shield	Mist and Driers Switch	8	1	8
Power supply	Switch-mode supply 12 V, 600 W	Power Supply	65	1	65
Hair dryer	Mondial Max Travel SC-10 Bivolt	Hot Wing Production	20	2	40
Mini cooler	Cooler 7 mm for Raspberry Pi (30×30×7 mm, 5 V)	Mist Removal	6	2	12
Ultrasonic humidifier	Ultrasonic piezoelectric humidifier (24 V)	Mist Producer	18	2	36
Aluminum square tube	Aluminum tube (5 cm × 5 cm × 20 cm)	Water storage	5	2	10
			Estimated total cost (U$)		**257**

play the videos and render the sensory effects synchronized with the audiovisual content. We chose these software packages because they offer open source access, support seamless integration of new devices, and render the sensory effects described in MPEG-V. The video player reads the SEM and sends it to the renderer, which was modified to parse and trigger thermal effect instructions. Specifically, the PlaySEM SER has been extended to support two new effect types (`hot_wind` and `cold_wind`), in addition to the RGB color light, wind and vibration effects already provided by that renderer [Santos *et al*., 2015]. All these effects were mapped to the microcontroller's corresponding control signals that activate the thermal devices. These additions were implemented according to the MPEG-V metadata structure.

Regarding mulsemedia content, two full HD videos at 30 fps were used (refer to Figure 4). The first video, titled *Sandboarding*, with 36 s, presents a first-person perspective of sandboarding. The second video, titled *Snowboarding*, lasting 29 s, depicts a similar sport carried out on snow-covered slopes. To examine the thermal sensations elicited by hot and cold airflows, the *Sandboarding* and *Snowboarding* videos were annotated with the effects of warm and cold wind.

4.1 Participants

This study was approved by the Research Ethics Committee of Brunel University London, protocol number 40020-LR-Oct/2022-41826-3. All participants provided their informed written consent before participation and were free to withdraw without penalty.

After the Ethics Committee approved the recruitment process, it started with a multifaceted approach. In this scenario, participants were invited through direct interactions. In addition, emails were sent to reach potential participants who may not be immediately accessible in person. At the end of this process, 12 participants (8 men and 4 women; average age $= 27.83$ years; standard deviation $= 5.621$) were included in the experimental group, all recruited by purpose sampling at the Federal University of Espirito Santo (UFES) and the Espirito Santo Research and Innovation Foundation (FAPES), both institutions located in Vitória-ES, Brazil.

Precautions were taken to ensure participant safety. The hot and cold airflow temperature range was previously calibrated during pilot tests to remain within safe and nonirritating thresholds. The duration of exposure to thermal effects was limited to brief intervals synchronized with video segments, avoiding continuous airflow. All sessions were supervised and participants were encouraged to report any discomfort or request a termination of the session at any time. No adverse effects were reported during or after the experiment.

4.2 Setup and Questionnaires

Upon arrival, participants received a final briefing and were allowed to address any remaining questions. Subsequently, they were comfortably seated and provided a comprehensive explanation of the experiment, which included its objectives, procedures, and ethical considerations. To ensure a thorough understanding, participants were prompted with clarifying questions before obtaining their informed consent.

Considering that air temperature perception is affected by the distance between thermal emitters and the user, Saleme *et al*. [2023] conducted a series of experiments to evaluate the variation in the thermal effects of TWIRL as a function of the distance between the emitter and the user. For hot airflow, the temperature decreased from 35 °C at 15 cm to 32 °C at 100 cm. In contrast, cold airflow exhibited temperatures ranging from 25 °C to 27 °C throughout the same distance interval. All measurements were performed at a controlled ambient temperature of 28 °C. The study further recommends that, in monitor-based setups, thermal devices should be aligned with the display screens, with the user placed at an approximate distance of 50 cm, to enhance her/his experience. In addition, user safety must be prioritized, particularly in scenarios where shorter distances may intensify thermal effects, to mitigate the risk of thermal discomfort or potential harm.

The participants were then placed as shown in Figure 5. During the evaluation, participants watched the videos *Sandboarding* and *Snowboarding*, in a randomized order, from 60 cm away from the screen and the TWIRL setup.

After viewing each video synchronized with haptic effects, the participants completed a series of questionnaires. Specifically, three different questionnaires were administered (see Table 2): the first aimed to evaluate the cold wind experience (Q1 to Q5), the second focused on evaluating the warm wind experience (Q6 to Q10), and the third addressed general aspects of the TWIRL system (Q11 to Q17), where participants provided feedback after the experiment.

Figure 5. Both cold wind towers were positioned on the side of the screen, in which the videos are presented, with the hairdryers standing slightly further behind.

The participants responded to each question using a Likert Scale ranging from *Strongly Disagree* to *Strongly Agree*, respectively, coded with values of 1 to 5 for analysis purposes. All evaluations were performed in an acclimatized room with an average temperature between 22 °C and 24 °C.

The questionnaire elements were adapted from previous mulsemedia and sensory effect evaluation studies Covaci *et al*. [2019, 2018]. Although no formal standard protocol was used, the questions were designed to reflect commonly used dimensions in user experience research, including perceived realism, distraction, enjoyment, and future intention of use. The Likert scale format (1-5) was selected to facilitate statistical aggregation and to align with previous studies in this domain.

To ensure the reproducibility of our experiment, we have made all supporting materials publicly available. This includes the two videos used in the user study (Sandboarding and Snowboarding), their respective SEM annotation files, design files for cold and hot wind devices, the Arduino microcontroller code, and detailed replication instructions. These resources can be accessed at: `https://github.com/lprm-ufes/TWIRL-SEM-Thermal-Playback.`. Accessed on August 16, 2025.

Table 2. User Evaluation Questionnaire.

Question Statement (Hot Wind)	
Q1	The hot wind effects enhance the realism of the experience.
Q2	The hot wind effects are distracting.
Q3	The hot wind effects are annoying.
Q4	I enjoyed the video incorporating hot wind effects.
Q5	I was comfortable with the intensity of the hot wind.
Question Statement (Cold Wind)	
Q6	The cold wind effects enhance the realism of the experience.
Q7	The cold wind effects are distracting.
Q8	The cold wind effects are annoying.
Q9	I enjoyed the video incorporating cold wind effects.
Q10	I was comfortable with the intensity of the cold wind.
Overall Experience	
Q11	I found the TWIRL experience engaging.
Q12	The noise level of TWIRL was bothersome.
Q13	I believe I would have fun using TWIRL.
Q14	I believe I would find using TWIRL enjoyable.
Q15	Using TWIRL will be exciting.
Q16	I would recommend TWIRL to my friends.
Q17	I would use TWIRL in the future.

Table 3. Reliability Coefficients.

Coefficient	**Value**
ω_h (Omega Hierarchical)	0.711
$\omega_{h\text{-asymptotic}}$ (Omega Hierarchical Asymptotic)	0.793
ω_t (Omega Total)	0.897
α (Cronbach's Alpha)	0.800

4.3 Data Analysis and Results

Employing the *reliabiliPy* tool on our results, we derived the following outputs relevant to our questionnaire responses. As summarized in Table 3, the reliability coefficients demonstrate the robustness of our questionnaire design.

Consequently, the values of 0.711 for the Omega Hierarchical (ω_h) coefficient, of 0.793 for the Omega Hierarchical Asymptotic ($\omega_{h\text{-asymptotic}}$) coefficient and of 0.897 for the Omega Total (ω_t) coefficient all indicate high reliability, with all factors accounting for almost 90% of the variance of the score. Moreover, a computed Cronbach's Alpha (α) of 0.800 also confirms the internal consistency.

As highlighted in Table 4, our user evaluation results are highly positive (it is worth noting that Q2, Q3, Q7, Q8, and Q12 are statements of negative phrasing). Consequently, for the hot wind effects, the participants found that they enhanced the realism of the experience (Q1), with most scores between 4.0 and 5.0. The effects of hot wind were not perceived as distracting (Q2) or annoying (Q3), as indicated by the low scores that disagreed with the statements in negative terms. The participants enjoyed the video with the effects of the hot wind (Q4) and were comfortable with the intensity of the hot wind (Q5). Similar results were obtained for participants' responses regarding the cold wind (Q6-Q10).

The distribution of responses can be visualized in Figure 6, which complements the summary statistics in Table 4.

Table 4. Summary of User Evaluation Results (average, median, and standard deviation) for Hot, Cold Winds and Overall Experience.

Question	AVG	Median	SD
Hot Wind			
Q1	4.42	4.50	0.67
Q2	2.75	3.00	1.22
Q3	2.00	1.50	1.21
Q4	4.58	5.00	1.00
Q5	4.33	5.00	1.07
Cold Wind			
Q6	3.92	4.00	0.79
Q7	1.67	1.50	0.78
Q8	1.17	1.00	0.39
Q9	4.25	5.00	1.29
Q10	4.67	5.00	0.65
Overall Experience			
Q11	4.42	5.00	0.90
Q12	2.25	2.00	0.97
Q13	4.08	4.00	0.90
Q14	4.58	5.00	0.51
Q15	4.42	4.50	0.67
Q16	4.25	4.00	0.75
Q17	4.33	4.50	0.78

Regarding the overall experience, the participants found the TWIRL experience engaging (Q11), did not find the noise level bothersome (Q12), and found using TWIRL to be fun (Q13), enjoyable (Q14) and exciting (Q15). Lastly, the participants indicated that they would recommend TWIRL to their friends (Q16) and use TWIRL in the future (Q17).

In summary, the quantitative results indicate a positive perception of the TWIRL system. Participants consistently rated the hot and cold airflow effects as realistic and pleasant, while reporting minimal distraction or discomfort. In particular, low average scores on negatively phrased questions (e.g., Q2, Q3, Q7, Q8) suggest that the airflow effects were well integrated into the viewing experience. The high scores for questions related to enjoyment (Q4, Q9), comfort (Q5, Q10), and engagement (Q11–Q15) further highlight that thermal wind stimuli contributed meaningfully to the multisensory experience. Although the study did not include open responses, the consistency in scores in multiple dimensions points to a coherent and immersive experience facilitated by synchronized thermal and audiovisual stimuli.

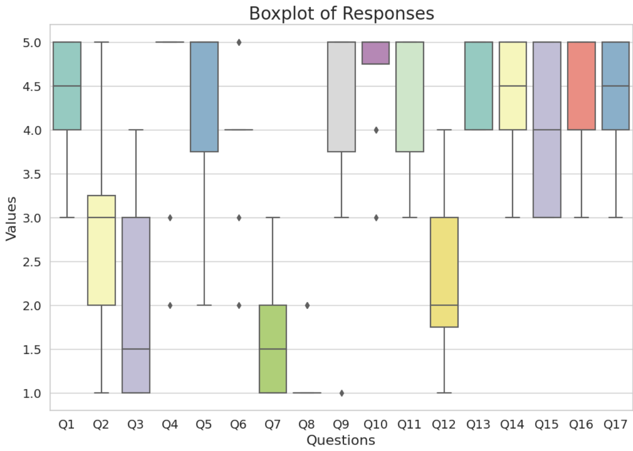

Figure 6. Questionnaire results

5 Discussion

This study presented TWIRL, a DIY system that delivers synchronized hot and cold airflows along with audiovisual content. Through a user-centered evaluation, we explored how temperature-controlled wind stimuli influence user perception of realism, enjoyment, and engagement in multimedia experiences.

Our participants positively responded to the TWIRL system in our evaluations. The hot and cold thermal effects were well received and contributed meaningfully to the immersive experience. Participants rated the experience as pleasant, comfortable, and engaging, suggesting that synchronized thermal stimuli can improve media experiences.

Although this study investigates aspects of user experience, such as comfort, enjoyment, and future use intentions, it is primarily done through the lens of usability and acceptance. A more nuanced analysis that includes emotional engagement, sensory realism, and long-term memory recall would further enrich our understanding of mulsemedia effectiveness and user engagement.

5.1 Limitations

Our study is not without limitations, and, as we discuss, although we were able to gather positive input, some flaws were also identified.

First, the participant sample was relatively small ($N = 12$) and was recruited from a general university population. Most participants had minimal prior experience with mulsemedia or thermal wind systems, which may have amplified the novelty effect and influenced subjective evaluations. Future studies should include larger and more diverse participant groups to improve generalizability.

Second, the absence of a control group prevents strong causal inferences about the contribution of thermal effects. All participants experienced synchronized hot or cold airflow with multimedia content, making it difficult to isolate the impact of the TWIRL system from that of the audiovisual content alone. Including a no-effect control condition would significantly improve the internal validity of future evaluations.

Third, our study used only semantically congruent pairings (e.g., hot wind with *Sandboarding* clip, cold wind with *Snowboarding* clip). Although this design supports ecological validity, it limits our understanding of how incongruent stimuli, such as hot wind during a snow scene, affect user perception. Future research should investigate such crossed stimuli to explore whether user responses are driven by sensory congruence or intrinsic effect qualities.

Fourth, the evaluation relied solely on closed-ended Likert scale items, which limits the ability to explore individual variations and unanticipated insights. The absence of open-ended questions or post-test interviews constrains qualitative interpretation. Incorporating semi-structured interviews or open-ended survey responses could yield richer feedback and deeper insights into user perception.

Fifth, although our questionnaires demonstrated good internal reliability, they were custom built ad hoc for this study, although based on standardized user experience models. Using validated instruments such as the User Engagement Scale (UES) [O'Brien and Toms, 2010] or the Technology Acceptance Model (TAM) [Davis, 1989] would strengthen future studies by supporting comparability and methodological rigor.

Finally, the experimental setup may have influenced the strength and directionality of airflow perception, including the spatial positioning of the emitters (cold wind towers placed laterally and hot wind emitters behind the participant). Future work should systematically evaluate how emitter placement (frontal, lateral, and peripheral) affects spatial realism and user comfort.

5.2 Future directions

The study opens several future directions to build on the results and address the limitations identified in the previous section.

First, experimental designs should include control groups and larger and more diverse sample sizes of participants to improve generalizability and causal validity of the findings. Including congruent and incongruent thermal-video pairings will enable investigation into how sensory alignment affects immersion and engagement.

Second, a mixed method that integrates open questions or semi-structured interviews with quantitative analyses should be used, as this combination could foster a more comprehensive understanding of user experiences and enable the identification of emerging themes.

Although no immediate risks were identified in this short-term study, future applications of TWIRL, particularly in prolonged or unattended settings, should consider guidelines for safe exposure durations and thermal intensities. Prolonged exposure to wind, thermal or not, can cause dryness in the eyes and throat. Factors like these should be carefully considered when dealing with extended exposure in systems such as TWIRL and setups alike.

From a technical point of view, improving the synchronization of thermal stimuli, especially given delays in the generation and dissipation of airflow, remains a challenge. Like olfactory effects [Ghinea and Ademoye, 2012; Murray *et al.*, 2013, 2014], thermal stimuli also require synchronization strategies. Investigating appropriate timing models could improve the precision and user perception of realism.

The scaling of the system also warrants investigation. Scaling TWIRL for larger or 360-degree configurations could enhance spatial immersion but introduces challenges in airflow consistency, intensity control, and directional accuracy [Tolley *et al.*, 2019]. Miniaturization of hardware and optimization of emitter placement may support more flexible deployment.

Our experimental setup positioned the cold wind towers laterally and the hot wind devices posteriorly relative to the participants (Figure 5). This configuration probably influenced the perceived intensity and spatial coherence of the thermal effects, as the direction of the air flow affects sensory perception. For example, frontal positioning produces stronger thermal sensations because of direct facial exposure to airflow, while lateral/rear arrangements could better simulate environmental wind patterns. Future work should systematically evaluate how emitter placement (frontal, lateral, peripheral) affects perceived realism and comfort, considering scenarios where front-facing thermal cues might enhance contextual alignment with visual content.

It is important to note that while this study investigates aspects of user experience, such as comfort, enjoyment, and willingness to reuse, it does so through the lens of usability and acceptance. A more granular analysis of experiential dimensions, such as emotional engagement, sensory realism, and long-term recall, would benefit future work, enriching the understanding of mulsemedia effectiveness.

Moreover, future studies could benefit from videos that combine cold and hot airflow effects in a single sequence. Such experiments would enable a more nuanced investigation of how users perceive transitions between thermal stimuli and whether these transitions further enhance the realism and engagement of the experience.

Finally, the TWIRL platform could be extended to domains such as education and accessibility. For example, temperature-based cues could reinforce learning or serve as alert systems for users with sensory impairments [Mohana *et al.*, 2023]. Furthermore, integrating other modalities, such as olfactory stimuli [Narciso *et al.*, 2020], could further elevate immersion and realism.

6 Conclusion

This paper introduced TWIRL, a multisensory system that enhances audiovisual experiences through synchronized hot and cold airflow stimuli. The user-centered evaluation demonstrated that participants perceived the thermal effects as pleasant and nondisruptive, indicating the potential of TWIRL to enhance immersion in media experiences. Although the study is exploratory and includes certain limitations, it lays a solid foundation for further research into multisensory interaction, paving the way for more comprehensive and scalable multimedia systems.

Funding

This study was financed in part by the Coordination for the Improvement of Higher Education Personnel (CAPES, Brazil) – Finance Code 7.570688/2020-00 and 88881.689984/2022-01, National Council for Scientific and Technological Development (CNPQ, Brazil) – Finance Code 307718/2020-4 and Fundação de Amparo à Pesquisa e Inovação do Espírito Santo (FAPES, Brazil) – Finance Code 2021-GL60J.

Authors' Contributions

Aleph da Silveira and Celso A. S. Santos contributed to the conception of this study. Eduardo Correa Rodrigues was responsible for implementing the TWIRL prototype and conducting performance experiments with the system. Aleph Campos da Silveira is the main contributor and writer of this manuscript. All authors read and approved the final manuscript. The text was partially generated with the help of ChatGPT [OpenAI, 2025].

Competing interests

The authors declare that they have no competing interests. Specifically, they affirm that they have no affiliations, financial involvement, or personal relationships that could potentially influence the conduct or reporting of this study. This declaration is made to ensure transparency and maintain the integrity of the research.

Declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Cardin, S., Thalmann, D., and Vexo, F. (2007). Head mounted wind. In *Proceedings of the 20th Annual Conference on Computer Animation and Social Agents*, CASA 2007, pages 101–108. EUROSIS-ETI.

Chen, Y.-S., Theodore, G., Huang, J.-Y., Hsieh, C.-E., Han, P.-H., and Hung, Y.-P. (2024). Flowzen: Using hybrid-haptic and particle for enhancing immersive experience via continuous illusion of wind. In *ACM SIGGRAPH 2024 Immersive Pavilion*, SIGGRAPH '24, New York, NY, USA. Association for Computing Machinery. DOI: https://doi.org/10.1145/3641521.3664400.

Covaci, A., Ghinea, G., Lin, C.-H., Huang, S.-H., and Shih, J.-L. (2018). Multisensory games-based learning - lessons learnt from olfactory enhancement of a digital board game. *Multimedia Tools and Applications*, 77(16):21245–21263. DOI: https://doi.org/10.1007/s11042-017-5459-2.

Covaci, A., Trestian, R., Saleme, E. B., Comsa, I.-S., Assres, G., Santos, C. A. S., and Ghinea, G. (2019). 360° mulsemedia: A way to improve subjective qoe in 360° videos. In *27th ACM International Conference on Multimedia*, page 2378–2386, New York, NY, USA. ACM. DOI: https://doi.org/10.1145/3343031.3350954.

da Silveira, A. C., Rodrigues, E. C., Saleme, E. B., Covaci, A., Ghinea, G., and Santos, C. A. S. (2023). Thermal and wind devices for multisensory human-computer interaction: an overview. *Multimedia Tools and Applications*, 82(22):34485–34512. DOI: https://doi.org/10.1007/s11042-023-14672-y.

Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS quarterly*, pages 319–340.

Ghinea, G. and Ademoye, O. (2012). User perception of media content association in olfaction-enhanced multimedia. *ACM Transactions on Multimedia Computing, Communications, and Applications (TOMM)*, 8(4):1–19. DOI: https://doi.org/10.1145/2379790.2379792.

Han, S., Ahn, J., and Choi, S. (2024). Generating haptic motion effects for general scenes to improve 4d experiences. In *2024 IEEE International Symposium on Mixed and Augmented Reality*, pages 51–60. DOI: https://doi.org/10.1109/ISMAR62088.2024.00019.

Hosoi, J., Ban, Y., Ito, K., and Warisawa, S. (2023). Pseudo-wind perception induced by cross-modal reproduction of thermal, vibrotactile, visual, and auditory stimuli. *IEEE Access*, 11:4781–4793. DOI: https://doi.org/10.1109/ACCESS.2023.3236310.

IJsselsteijn, W. and Riva, G. (2003). Being there: The experience of presence in mediated environments. In *Being there: Concepts, effects and measurements of user presence in synthetic environments*, Studies in new technologies and practices in communication, pages 3–16. IOS Press, Amsterdam, Netherlands.

Mohana, M., da Silveira, A. C., Subashini, P., Santos, C. A. S., and Ghinea, G. (2023). Technology enhanced mulsemedia learning: Insights of an evaluation. In da Silva, H. P. and Cipresso, P., editors, *Computer-Human Interaction Research and Applications*, pages 24–42, Cham. Springer Nature Switzerland. DOI: https://doi.org/10.1007/978-3-031-49368-3_3.

Murray, N., Lee, B., Qiao, Y., and Muntean, G.-M. (2014). Multiple-scent enhanced multimedia synchronization. *ACM Transactions on Multimedia Computing, Communications, and Applications (TOMM)*, 11(1s):1–28. DOI: https://doi.org/10.1145/2645862.

Murray, N., Qiao, Y., Lee, B., Karunakar, A., and Muntean, G.-M. (2013). Subjective evaluation of olfactory and visual media synchronization. In *Proceedings of the 4th ACM Multimedia Systems Conference*, pages 162–171. DOI: https://doi.org/10.1145/2483977.2483998.

Narciso, D., Melo, M., Vasconcelos-Raposo, J., and Bessa, M. (2020). The impact of olfactory and wind stimuli on 360 videos using head-mounted displays. *ACM Transactions on Applied Perception*, 17(1):1–13. DOI: https://doi.org/10.1145/3385959.

O'Brien, H. L. and Toms, E. G. (2010). The user engagement scale: Developing a measure of user engagement. *Journal of the American Society for Information Science and Technology*, 61(1):50–69.

Ogiwara, Y., Suzuki, M., and Matsuura, A. (2020). Windtherm fire: An MR system for experiencing breathing fire of a dragon. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pages 567–568. IEEE. DOI: https://doi.org/10.1109/VRW50115.2020.00135.

OpenAI (2025). Chatgpt (april 2025 version). `https://openai.com`. Access on 24 September 2025.

Peiris, R. L., Peng, W., Chen, Z., Chan, L., and Minamizawa, K. (2017). ThermoVR. In *2017 CHI Conference on Human Factors in Computing Systems*. ACM. DOI: https://doi.org/10.1145/3025453.3025824.

Ranasinghe, N., Jain, P., Karwita, S., Tolley, D., and Do, E. Y.-L. (2017). Ambiotherm: enhancing sense of presence in virtual reality by simulating real-world environmental conditions. In *2017 CHI Conference on Human Factors in Computing Systems*, pages 1731–1742. DOI: https://doi.org/10.1145/3025453.3025723.

Ranasinghe, N., Jain, P., Tram, N. T. N., Tolley, D., Liangkun, Y., Tung, C. E. W., Yen, C. C., Do, E. Y.-L., Koh, K. C. R., and Shamaiah, K. (2018). A demonstration of season traveller. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM. DOI: https://doi.org/10.1145/3170427.3186511.

Rodrigues, E. C., Saleme, E. B., and Santos, C. A. S. (2021). A haptic system for switching wind temperatures based on ultrasonic vibrations, peltier elements, and electrical resistances for multisensory applications. In *Brazilian Symposium on Multimedia and the Web*, pages 73–80. DOI: https://doi.org/10.1145/3470482.3479638.

Saleme, E. B., Covaci, A., Mesfin, G., Santos, C. A. S., and Ghinea, G. (2019a). Mulsemedia diy: A survey of devices and a tutorial for building your own mulsemedia environment. *ACM Computing Surveys (CSUR)*, 52(3):1–29. DOI: https://doi.org/10.1145/3319853.

Saleme, E. B., da Silveira, A. C., Covaci, A., Ghinea, G., and Santos, C. A. S. (2023). Enhancing multisensory experiences through temperature-controlled wind effects. https://doi.org/10.21203/rs.3.rs-2556039/v1.

Saleme, E. B. and Santos, C. A. S. (2015). Playsem: A platform for rendering mulsemedia compatible with mpeg-v. In *21st Brazilian Symposium on Multimedia and the Web*, WebMedia '15, page 145–148, New York, NY, USA. ACM. DOI: https://doi.org/10.1145/2820426.2820450.

Saleme, E. B., Santos, C. A. S., and Ghinea, G. (2019b). A mulsemedia framework for delivering sensory effects to heterogeneous systems. *Multimedia Syst.*, 25(4):421–447. DOI: https://doi.org/10.1007/s00542-019-05002-7.

Santos, C. A. S., Rehem Neto, A. N., and Saleme, E. B. (2015). An event driven approach for integrating multi-sensory effects to interactive environments. In *2015 IEEE International Conference on Systems, Man, and Cybernetics*, pages 981–986. DOI: https://doi.org/10.1109/SMC.2015.178.

Sardo, J. D., Pereira, J. A., Veiga, R. J., Semião, J., Cardoso, P. J., and Rodrigues, J. M. (2018). Multisensorial portable device for augmented reality experiences in museums. *International Journal of Education and Learning Systems*, 3.

Singhal, Y., Wang, H., and Kim, J. R. (2023). Fire: Mid-air thermo-tactile display. In *SIGGRAPH Asia 2023 Emerging Technologies*, SA '23, New York, NY, USA. Association for Computing Machinery. DOI: https://doi.org/10.1145/3610541.3614584.

Suzuki, M. and Matsuura, A. (2019). Windtherm: A wearable VR device that provides temperature-controlled wind. In *Proceedings of the 2019 Virtual Reality International Conference - VRIC*, pages 39–44. ACM. DOI: https://doi.org/10.1145/3314493.3314502.

Tolley, D., Nguyen, T. N. T., Tang, A., Ranasinghe, N., Kawauchi, K., and Yen, C.-C. (2019). Windywall: Exploring creative wind simulations. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction*, TEI'19, pages 635–644. ACM. DOI: https://doi.org/10.1145/3294109.3295624.

Wilberz, A., Leschtschow, D., Trepkowski, C., Maiero, J., Kruijff, E., and Riecke, B. (2020). Facehaptics: Robot arm based versatile facial haptics for immersive environments. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, CHI '20, page 1–14, New York, NY, USA. Association for Computing Machinery. DOI: https://doi.org/10.1145/3313831.3376481.

Xu, J., Hasegawa, S., Kiyokawa, K., Ienaga, N., and Kuroda, Y. (2023). Integration of independent heat transfer mechanisms for non-contact cold sensation presentation with low residual heat. *IEEE Transactions on Haptics*, 16(4):770–784. DOI: https://doi.org/10.1109/TOH.2023.3324754.

Zhao, F., Li, Z., Luo, Y., Li, Y., and Liang, H.-N. (2024). Airwhisper: enhancing virtual reality experience via visual-airflow multimodal feedback. *Journal on Multimodal User Interfaces*. DOI: https://doi.org/10.1007/s12193-024-00438-9.