# VaiR: Simulating 3D Airflows in Virtual Reality

**Michael Rietzler**          **Katrin Plaumann**          **Taras Kräenzle**          **Marcel Erath**
**Alexander Stahl**          **Enrico Rukzio**
Institute of Mediainformatics, Ulm University, Ulm, Germany
firstname.lastname@uni-ulm.de

## ABSTRACT

The integration of multi-sensory stimuli, e.g. haptic airflow, in virtual reality (VR) has become an important topic of VR research and proved to enhance the feeling of presence. VaiR focuses on an accurate and realistic airflow simulation that goes far beyond wind. While previous works on the topic of airflow in VR are restricted to wind, while focusing on the feeling of presence, there is to the best of our knowledge no work considering the conceptual background or on the various application areas. Our pneumatic prototype emits short and long term flows with a minimum delay and is able to animate wind sources in 3D space around the user's head. To get insights on how airflow can be used in VR and how such a device should be designed, we arranged focus groups and discussed the topic. Based on the gathered knowledge, we developed a prototype which proved to increase presence, as well as enjoyment and realism, while not disturbing the VR experience.

## ACM Classification Keywords

H.5.2. User Interfaces: Haptic I/O; H.5.2. User Interfaces: Prototyping

## Author Keywords

Virtual reality; airflow; presence; evaluation.

## INTRODUCTION

Enhancing presence and immersion is one of the major goals of Virtual Reality (VR) research. The sense of *being there* [7] both occurs and can be supported in three dimensions: the personal, the environmental and the social forms of presence. The main focus of this paper is to enhance the personal feeling of presence. This can be achieved by simulating sensory stimuli as close as possible to the capability of a sensor regarding range and intensity. Appealing multiple senses amplifies the feeling of presence and immersion in VR applications [3, 6]. Besides the inherent integration of visual and audio [9, 13] in most VR systems, a large body of work exists to include further channels in the VR experience. Those channels include haptics [1, 19], warmth [4, 5] and smell [21, 20]. Regarding

**Figure 1. The VaiR Prototype worn in combination with a HTC Vive head mounted display. Fixed to frame mounted onto the Vive's straps are two bows. These bows are moved by two separate motors, allowing both bows to each rotate 135°. Fixes on each bow are five nozzles (each 36° apart), were the air streams come out. Several nozzles can be used at the same time. Due to the modular design, nozzles can be moved along the bows and changed as needed. That way, angle and dispersion of the air streams can be customized. VaiR is so designed that a container of pressurized air, valves, power source and an arduino controller can be worn as a backpack.**

haptics, integration can be applied in different ways. In this paper, we focus on enriching haptics by simulating airflow accompanying visual and audio content.

Though simulating airflow, most of all in the form of wind, in VR has been researched in the past, little work regarding the conceptual side has been done. To fill this gap in knowledge, we conducted a series of three focus groups with participants of various VR literacy. In those focus groups we explored how, where, and in which situations air streams could be leveraged to enrich VR experiences. The discussions showed that airflow simulation can go far beyond the simulation of wind, reaching from realistic effects to unrealistic superpowers for gaming. Many desired applications need to be applied with less delay

as possible and have to be precise or even animated in the three dimensional space.

The results of the focus groups led to the design of a prototype wearable on ones head. The proposed prototype, as shown in Figure 1, can easily be combined with current head mounted displays. It also allows three dimensional airflow simulation with a reaction time of less then 20 milliseconds until stimulus. Air streams are pneumatically generated, allowing a maximum air speed of around 25km/h. The advantages of using pneumatics translate in the size and weight of the prototype as well as the reaction time and maximum air speed that can be applied to the user. Prior systems either used a static wearable or a completely stationary approach, which both restricts the accurate animation of wind sources and do not support temporary effects like gusts due to too much delay.

The short reaction time of VaiR also offers new possibilities of staging a VR experience, since the duration of applied air pressure and its intensity is variable and responds within milliseconds to changes. This allows to use VaiR as both, an effect channel to directly support visual or auditive stimuli (e.g. the blast of an explosion), as well as a tool to simulate more steady conditions (e.g. wind at a coast). The movable bows on which the nozzles are mounted can rotate in angles of 270 degree of freedom, which can be e.g. used to follow animations of objects, like a helicopter flying over the user's head.

In a user study we analyzed how presence and enjoyment were affected by incorporating the wind models in four scenarios involving wind resulting form users' movements, static wind sources, a combination of both and air streams underlining certain effects. Our results on one hand support the results of prior works showing an increase of presence using airflow in VR. On the other side we could show that enjoyment is influenced even more.

The contributions of this paper can be summarized as conceptual, technical and empirical. First, the results of the focus groups provide conceptual insights in how diverse user groups could benefit from airflow simulation in VR. Second, the proposed prototype is the first mobile pneumatic airflow simulator designed for VR. We also introduce new features, including rotatable bows and short reaction times. And third, our empirical study, which showed how wind can enhance presence and enjoyment, including four different scenarios using different airflow sources and features.

## RELATED WORK
There are several ways of generating air streams. The related work follows two major approaches: static sources placed around users, and systems mounted on users' head.

### Static Sources
Deligiannidis et al. [2] used a stationary fan in front of the user to simulate the airflow of driving a scooter while traveling through a large scale virtual environment. They observed an increase of immersion when using the wind simulation. Moon et al. [16] presented WindCube, a wind display for VR applications. They used multiple fans placed in the users'

surrounding to provide a three-dimensional wind experience. In their evaluation, participants could not distinguish wind sources having less gap than 45°. They also report a significant increase of subjective presence using wind.

Verlinden et al. [18] built a virtual sailing environment using eight static fans. Their evaluation results show an improved immersion when using wind. Participants suggested several improvements to the system, including higher airflow disparity, higher wind resolution, and reduction of noise. Pluijms et al. [17] used the same simulator to measure how good humans can distinguish different directions and strengths. The participants were expert sailors as well as non-sailors. Their results indicate, that the direction can be recognized more precise for frontal wind directions than for wind from behind. Wind was also perceived faster when impinged frontally.

Kulkarni et al. [12] enhanced a VR-cave with a very accurate wind simulation using vortices of airflow and applied a similar approach to their TreadPort Active Wind Tunnel (TPAWT) [11]. The TPAWT integrated locomotion interfaces as well as other sensory outputs like visual, auditory or olfactory. The design of the TPAWT allows each fan to produce a distributed full-body experience, similar to real wind.

Hüllsmann et al. [8] enhanced a cave by adding fans and lamps to simulate wind and warmth. Both influenced the subjective presence of participants. They also state a reaction time of their setup with around 3.1 seconds when turned on and 1.3 seconds when turned off.

Our prototype differs from the above mentioned work in three ways: First, we use pneumatic wind generation, leading to far less delay (below 2 ms). Second, our prototype is designed for mobile use. And third, through the movable bows our prototype allows more variable wind positions and even animations of wind wind sources.

### Head Mounted Sources
Kojima et al. [10] described a wearable helmet that consists of four audio speakers that produce wind that is forwarded by tubes towards the user's ears, the region they found to be most sensitive. This wearable approach reduces the reaction times. They also state, that the region around the ear has a high spatial resolution of perception which would lead to a large number of wind sources. They evaluated the precision of wind localization of four participants, which indicated higher precision close to the ear.

Lehmann et al. [14] proposed both a stationary and a wearable approach of producing wind. Both approaches were implemented using two fans. As stated in other related work, the wind had in both cases a positive impact on presence. Yet, participants preferred the mobile over the stationary set-up.

Related work has proved, that a mobile wearable device can be build and is preferred by participants. Though there are no results on the implications and effects on immersive VR.

## FOCUS GROUPS: ON THE USE OF AIRFLOW IN VR
We were interested in the potential knowhow on how to design airflow in VR. Especially since using air streams was regarded

more as a technical challenge in prior work, we aimed at getting insights on potential application and use cases but also on technical requirements. Thus, we conducted a series of three focus groups, each consisting of participants from the VR user groups VR consumers, VR developers and VR researchers. In each focus group, we asked participants what potential they saw in airstreams in VR, which scenarios they imagined, and how such a device should be designed and implemented. Afterwards, the prototype was presented to each focus group. In an open discussion, the aforementioned topics regarding design and implementation as well as usage scenarios were revisited.

### Participants

Participants were recruited through flyers and personal contact. For the VR consumer group, we recruited 5 participants. The average age was 23.8 years (2.45 SD), participants were students of computer science. VR consumers are mostly users of VR, without having developed VR applications. VR developers were participants who developed VR applications for at least a year on a regular basis, for examples games, without researching VR as such. We recruited 4 developers, with an average age of 26.5 (3.1 SD). The respective group included developers with focus on serious games, driving simulation and storytelling. Researching VR as such was a criterion for participants in the VR researcher group. Here, we recruited 5 participants (four of them HCI and one psychologist), at average 29.6 (7.23 SD) years old. All participants gave consent and received 5 €compensation. Each focus group took about one hour.

### Results

The recordings of the focus groups were transcribed verbatim. Subsequently, three researchers performed an open coding on the transcript of the first focus groups (VR consumers). The codes were compared, conflicts were resolved with discussions and revisiting of the transcript. Following, the other two focus groups were coded in the same way. If agreed upon, codes from the first focus group were used, if not, new codes were created. Conflicts were solved through discussion and revisitation of transcripts. This way, we gained a codebook applicable to all three focus groups. Based on the initial codes, axial coding was performed to find themes and concepts. Namely, we identified the three categories: requirements, applications and experiences.

#### Requirements

Modelling the wind concerns either how wind should be rendered, but also how practitioners wished to be able to include it in their applications. Regarding the rendering of wind, it should be as realistic as possible, including dynamic aspects like gusts, precision, direction changes and reaction time. Developers expressed the need for a simple interface, preferably integratable in existing developing environments, and design guidelines covering how to provide the best experience.

#### Applications

Participants saw wide ranges of applications for wind in VR. Those applications ranged from realistic ones to unrealistic ones. Application areas covered entertainment, simulation,
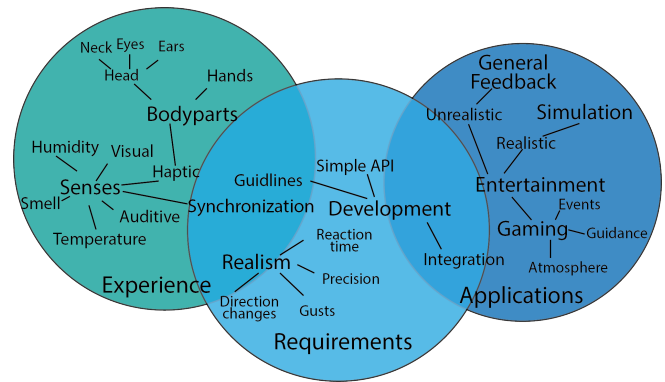


Figure 2. Overview of the focus group results.

and feedback. In case of applications falling in the entertainment area, participants liked both realistic and unrealistic air stream simulations. Realistic rendering of air streams could amplify events, examples mentioned by developers include pressure resulting from explosions as well as weather conditions. Unrealistic air streams could be leveraged as representations of super powers in games, or represent energy states of players. Air streams were further regarded useful when guiding users attentions, e.g. to make them aware of risks or points of interest, or to render elements were users could not see them, e.g. the breath of a monster behind a player. Generally, air streams were seen useful in games, to raise the experience.

Participants found air streams useful for enriching different simulations, covering simulations of environments like cliffs, seas, and deserts. Air streams could also be useful in sales simulations. Other types of simulations used air streams to underline the users movements, e.g. while riding a bicycle, driving in a convertible, riding a roller coaster or flying. Further, air streams were seen as useful for giving haptic feedback to users, e.g. for guiding users or simulating barriers as mentioned by one of the developers.

#### Experience of wind

Regarding the experience, focus group participants were concerned with the body part air streams are perceived most with as well as the synchronization with other channels. Regarding the body parts, most important were hands and head, were people usually do not wear cloths and thus feel real air streams more. Furthermore, head regions were of particular interest to participants. They explicitly mentioned several regions (neck, eye region, ears) of interest, since they were either important for certain use cases or seen as particularly sensitive for air streams. Additional to the region air streams were applied on, it was seen as important to synchronize them with other channels. Those channels covered especially audio, but also visual. During the discussion, other not yet implemented modalities like temperature, smell and humidity came up and were discussed by researchers and developers. Those were seen as closely linked with air streams, and could enrich and complete the experience even further. Examples for this included simulation of environments, like hot dry air in deserts, and humid and salty air at coasts. The researcher group also discussed
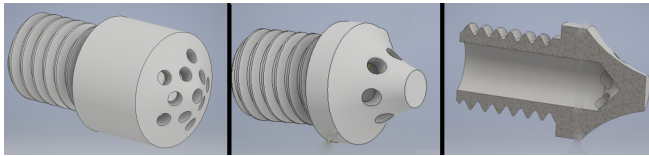
Figure 3. Examples of different nozzles to vary spray angle and intensity.

the potential problem of wearing VR glasses that mask large parts of the face. They suggested to use visual cues like a virtual character wearing glasses to enhance the experience. The same could also be done if the hands were not stimulated by airflow by having the character wearing gloves.

### IMPLEMENTATION

The prototype consists of two main technical components, one being the head mount, and the second being a backpack including the logic board and valves to control the system. The software consists of two parts, a Unity plug-in that translates positions, angles and intensities into the the VaiR coordinate system and streams the respective data to the logic board (either via Bluetooth 4.0 Low Energy, or using the serial port). The prototype can therefore be used for sitting as well as mobile VR experiences.

### Technical setup

Participants of the focus groups as well as related work suggest, that the region being most important for airflow application is the head region. Considering other found requirements like synchronization, fast reaction time and the possibility of simulating non constant airflow finally led to the desing of our pneumatic head mounted device. The use of fans, which have to be turned on and off takes too long would not meet the defined temporal requirements. To reduce the weight of the prototype, the setup mounted on the head was reduced to a minimum, consisting of two bows (each having 5 nozzles with an angular distance of 36°). We decided to use an angular distance of 36° instead of the proposed 45° since the latter would lead to a single nozzle pointing towards the ears. Since literature and related work emphasizes the importance of the ears for directional perception, the 36° arrangement enables to stimulate the ear region with nozzles per ear. We also designed a variety of nozzles with different spray angles as well as a different amount and diameter of holes. The different nozzles could be used to simulate different airflow sources. In our testing a triangular shape provided the best area to intensity ratio, which was important since hair blocked a fair amount of the wind intensity. The nozzles are mounted on the bows with a custom printed holder using threads to allow quick swapping for testing and to fit into the idea of a modular design. Some examples are shown in figure 3. The bows are rotated by two servo motors. To mount the setup on the user's head, a retainer which connects the components is located in the middle of the setup (see figure 4). The control unit is worn as a backpack for mobile scenarios, or can be placed anywhere within the user's reach. A Redbearlab Blend, a development board with BLE 4.0 support for mobile was chosen as central processing unit. The board controls the motors rotating the bows, as well as 14 valves, ten applied to the tubes attached to the nozzles on the bows and four as exhaust air valves to vary the pressure and
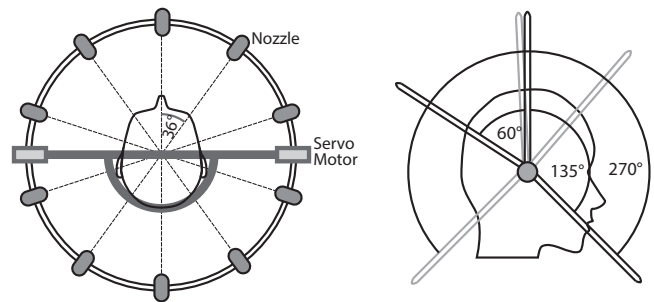


Figure 4. The VaiR setup: Two bows with nozzles having a angular distance of 36° and two servo motors to control the angle of each bow seperately (left). Each bow can be rotated 135°, overall 270° around the user's head and neck can be displayed (right).
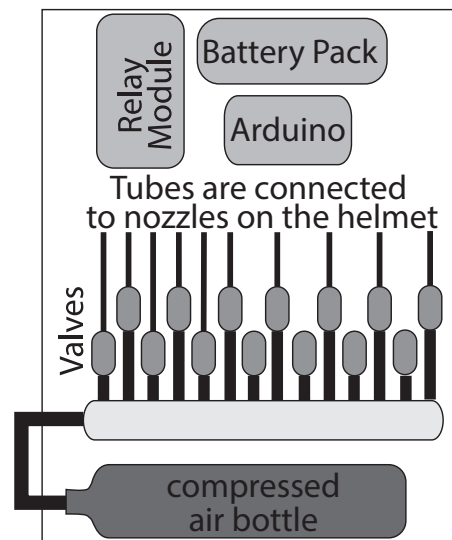


Figure 5. The Backpack consists of a compressed air bottle and 14 valves (ten for the nozzles, and four to vary the intensity) as well as the control unit.

therefore the air speed at the nozzles. The pressure of a maximum of 2 bar can be induced by e.g. compressed air bottles. The VaiR helmet is lightweight with around 766 g (compared to around 600 g of an HTC Vive), while the backpack currently weights about 4 kg. The current prototype consists of two heavy PVC sheets on which the electronics and valves are applied. The weights could though be reduced by using more lightweight components and by using valve blocks instead of single valves. The helmet's measures were kept as close as possible to a user's head wearing current VR glasses, which lead to a diameter of around 21 cm. The backpack currently measures 40 cm x 25 cm x 15 cm, but could be designed much smaller in a second iteration.

### Unity3D Plug-In

The Unity3D plug-in consists of various airflow sources (static sources, effect sources and sources modeling the airflow of a moving user). A source can be configured by a set of attributes. These are e.g. the speed or the intensity of the modelled gusts, as well as the horizontal or vertical angles and a maximum distance.

Static sources can be used to model airflow of long term sources, which can be wind, a ventilator or a helicopter. Effect sources are triggered and the effect lasts for a defined time frame and are used as (repeated) short term sources, e.g. for firing a gun or support game effects like an explosion. All attributes can be staged by using scripts or animations.

For the calculation of the entry angle of airflow, the 3D coordinate system is split in two – a horizontal and a vertical angle. On hardware side, the horizontal angle is represented by the nozzles and the vertical one by the angle of the bows. The angular distance of the nozzles is $36°$. Defining the origin of a nozzle as angle zero, each nozzle is used to simulate a source within an angular distance of $±18°$. The horizontal entry angle is calculated by using the position of the source ($P_S$) and the position of the user ($P_U$) as well as the user's viewing direction as a quaternion ($Q_U$. The entry vector ($V_E$) and the horizontal and vertical angles ($A_H$, $A_V$) are calculated as follows:

$$V_E = Q_U^{-1} \cdot (P_U - P_S) \tag{1}$$

$$A_H = \arccos(\begin{bmatrix} 0 \\ 1 \end{bmatrix} \cdot \begin{bmatrix} V_E.x \\ V_E.z \end{bmatrix}) \cdot \frac{180}{\pi} \tag{2}$$

$$A_V = \arccos(\begin{bmatrix} 0 \\ 1 \end{bmatrix} \cdot \begin{bmatrix} V_E.y \\ V_E.z \end{bmatrix}) \cdot \frac{180}{\pi} \tag{3}$$

The horizontal angle is then mapped to the matching nozzle, and the vertical one is translated into the bow's coordinate system. If the speed is influenced by the distance, the loss of speed is interpreted as a linear mapping of distance to speed until reaching zero. Since the user will have to wear VR glasses, parts of the face are occluded and therefore no longer able to feel the stimulation of airflow. We therefore left out the respective angles. The bows keep resting on top of the glasses or below, depending on the calculated angle.

**Design Space and applications**
The short reaction time as well as the rotatable bows – allowing animated airflow sources as well as a 3D experience –, as well as the strong maximal wind speed of around 25 km/h makes the VaiR system suitable for a variety of applications and opens a large design space.

Static sources, like a global wind, that can be staged more realistic by simulating gusts, while even strong wind of over 25 km/h can be displayed. But also non static sources, like a rotatable ventilator can be simulated, by changing vertical angles by rotating the bows, or by changing horizontal angles by using different nozzles. A helicopter may fly over the user's head, where the gust property can be used to simulate turbulences of the rotor blades and the position of the helicopter is represented by the bow angles and the used nozzles.

Besides such sources which involve longer durations, it is also possible to apply short term effects. While playing a shooter for example, short blasts can support the feeling of shooting a gun, or simulate the shock wave of an explosion.

Since the VaiR system enables the simulation of two independent sources at a time, it is also possible to stage an experience with multiple effects, or a constant source with additional effects using short term blasts. When wearing the backpack, it is also possible to have a mobile experience using e.g. the HTC Vive.

**EVALUATION**
Since the main focus of the VaiR prototype is to enhance the feeling of presence and the enjoyment while consuming VR content, we focused our evaluation on these two factors. We developed four different Unity scenes, each of them having a focus on a different kind of airflow source. To exclude side effects which could arise by a user interacting in a different way, we decided to design the conditions passive only, with the user taking part as observer. This design ensured on one hand that the sequence of events was determined and equal for each participant and on the other hand excluded side effects on presence and enjoyment which could occur due to different behavior.

**Participants**
Overall 24 participants (20 male and four female, aged 20 to 36 – mean: 26) took part in our evaluation. Each of them was compensated with 10 €. We asked them to describe their previous experience with virtual reality on a five point Likert scale (from 0: no experience to 5: very experienced). The answers were evenly distributed with a mean of 2.7 and a standard deviation of around 1.5. There were as many novice VR users as experienced ones.

**Scenes**
We developed four different Unity3D scenes that allowed the participants to passively consume the VR content, without any distracting interactions. All scenes are shown in figure 6 and 7.

The first scene takes the participants to a cliff at the seaside. While standing right in front of the edge, the user can turn around facing the sea, where a static wind source is placed, which is simulating wind that blows from across the sea. The wind is modelled using weak gusts and an average wind speed of around 20 km/h. When turning one's back to the sea, a landscape with trees waving in the wind and small hills is presented.

In the second scene, the participants find themselves sitting in a fun ride in a fair scenario. The camera is placed in a cabin attached on the end of a rotating arm. The cabin, and therefore the participant's orientation was always horizontal to prevent sickness. The direction of the wind varied according to the cabin's movement, which was a circular one. The wind speed also varied according to the movement speed, with a maximum of around 25 km/h.

The third scene is staged in a windy and foggy area. The viewer sits in a golf cart, driving through the area. There are two different wind sources that can be felt at the same time. The first being the airstream of the moving cart blows in the inverse driving direction, while the second one is a static wind source located far behind the cart, on the right side. The far
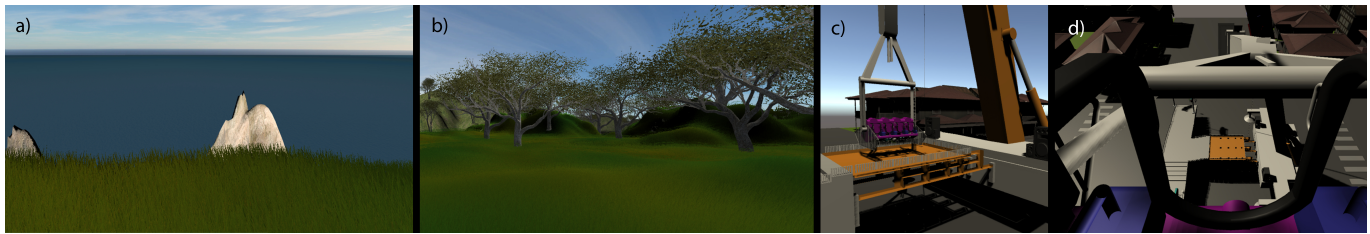
**Figure 6. The first and second scene used for the evaluation. a) The cliff scene looking towards the sea and b) view when turned around. c) The fair scene regarded from outside and d) the first person view. e) The golf cart scene from first person view.**
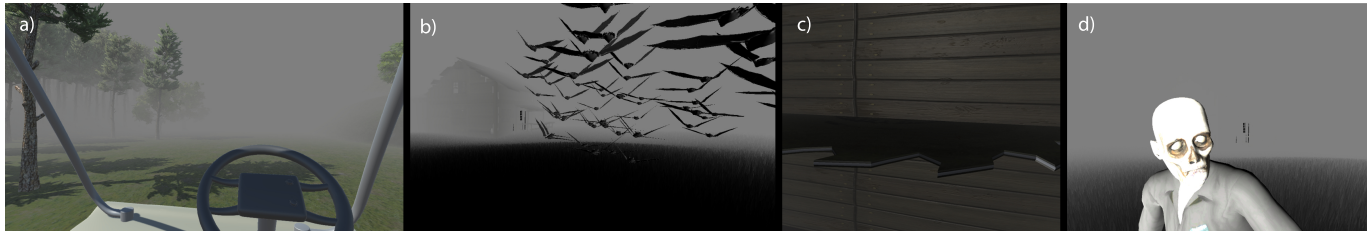


**Figure 7. The third and fourth scene used for the evaluation. a) The cart scene in first person view. b) The horror scene: bats flying over the head, c) a rotating saw runs through the viewer's neck and d) a Zombie appears.**

distance allows the simulation of wind, with a constant global wind direction – independent of the actual position of the cart.

The last scene was the most complex one and most of all is based on the ideas gathered in the focus groups. The participants reported many use cases of airflow as an effect source and mentioned different examples in horror scenarios, like bats flying over the user's head, or non visual experiences including audio and airflow.

The scene starts at a foggy and gloomy place, with a wooden hut in the distance. There is a constant wind source blowing from behind, while a second wind source is used as an effect channel, supporting events. The first event is a group of bats flying from behind over the users head. The effect wind source starts behind the user and moves until coming from front. To simulate the strokes of the wings, this source has a high gust intensity. The wind therefore varies in speed and angle over time. The second event is a kind of zombie that comes closer in large steps, when he arrives directly in front of the user, a short and strong wind is applied to support the shocking moment. Then the virtual camera *runs* towards the hut. The movement is again supported by air stream, while the static wind source still blows from behind. When entering the hut, the visual image turns to black. Only the audio of a monster breathing from behind can be heard – and felt, since every breath is supported by airflow. The last event occurs, when the lights turn on again and a giant saw is rotating in front of the camera, which can be felt by a gusty airflow source. The saw starts moving directly under the camera, simulating to get the head cut off while the wind source of the saw moves towards the user's throat.

As discussed in the focus groups, potential application areas can be found in entertainment (realistic and unrealistic) or simulations. Two of the chosen scenes were discussed in the focus groups. First of all the cliff, as an example of an environmental simulation. The second discussed one was the horror scene, which is also an example of an unrealistic

entertainment application. We furthermore wanted to cover different sources of airflow as discussed in the focus groups. External sources and ones induced by personal movements were both covered in the presented scenes. Since the fair covered the movements and the cliff scene the external one, the golf cart scene was chosen as combination of both, containing external wind as well as user's movements.

**Method**

We used a within subjects design, in which each participant was subjected to eight different treatments (four different scenes, either with the simulation of airflow or without). The sequence of the eight treatments was determined by a Latin Square to balance effects of adaption. To measure presence and engagement we used the $E^2I$ questionnaire [15] without the items concerning the memory task, since they are not relevant for the presented conditions. The $E^2I$ questionnaire has a separate presence and enjoyment score. While the presence score is determined by eight items, the enjoyment is the mean of four sub-scores.

**Procedure**

Each participant was welcomed and introduced to the subject of the evaluation and the procedure. Then the prototype was shown and the basic functionality described. After this, the participants signed a declaration of consent regarding the usage of the gathered information for scientific purposes and were then asked to complete a demographic questionnaire, including the items *age, gender* and *VR experience*. Afterwards, the participants were helped putting on the VaiR helmet, earphones and a Oculus Rift DK 2 as VR headset and started with the first treatment. Each sequence lasted for about 1.5 minutes. The participants completed the $E^2I$ questionnaire after each condition until the end of the procedure. Finally, each participant filled out a final questionnaire, consisting of information regarding general interest in airflow simulation in VR, and how much each scene was influenced by the use

of airflow. Each session lasted for about 40 minutes and the participants were thanked and compensated with 10 €.

## Results

The results presented in the next sections are based on the questionnaire results raised as described.

### Presence and Enjoyment

The $E^2I$ Questionnaire includes eight items regarding the presence. We excluded two of them, since one is focused on a memory task, and a second, that compares two different systems. The presence score is calculated by the mean of all related items, while the distraction factor is inverted. The treatment using the VaiR helmet proved to have a significant positive impact on the felt presence of the participants (Wilcoxon signed-rank test: Z=-2.362, p<.05).

To calculate the enjoyment score, the mean of four different items is used. It consists of questions like how sad the participant felt when the experience was over, how much he enjoyed it, if he wanted to repeat it and how interesting it was. There was a significant increase of enjoyment using the wind treatment (Wilcoxon signed-rank test: Z=-5.518, p<.05). Interestingly, the mean improvements regarding enjoyment were much larger then the improvements of the presence score. When comparing each scenes separately to the respective control condition without VaiR the increase of enjoyment remained significant on the 5% level using the Wilcoxon signed-rank test (cart: Z= -2.858, cliff: Z = -3.698, fair:Z = -2.393, horror: Z= -1.770).

In a next step we regarded the difference between the scenes – by comparing all the control conditions and the VaiR conditions separately. Where the presence was not significantly different on the 5 % level (p = .075) without VaiR treatment, we observed significant differences when VaiR was used (p = .009) using the Friedman two way analysis of variance by ranks. We could find the difference between the horror scene compared to all others using a Bonferroni post-hoc test. We could find the increase of presence being highest in the horror scene, while the other scenes did not differ.

We could not observe any significant differences between the scenes regarding enjoyment. Since we assumed, that the increase of presence would also lead to an increase of enjoyment, we took a closer look on the horror scene and found a great variance regarding the perceived enjoyment between the users in the VaiR condition. While some rated the enjoyment as three times as high as without, there were participants stating only half the enjoyment. We assume that the high variance arised by the different affinity towards horror in general which will be considered in more detail in the *Discussion* section.

### Distraction and Realism

We also regarded four items related to the subjective feeling of realism of the VR experience separately. Since the simulation of airflow is designed to increase the level of felt realism while consuming VR content, we compared the mean of the four sub-scores with and without VaiR. Again, the treatment with airflow simulation increased the perceived realism significantly (Wilcoxon signed-rank test: Z=-2.967, p<.05)
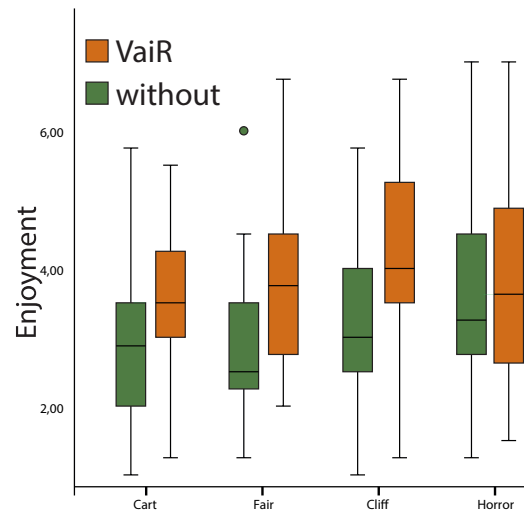


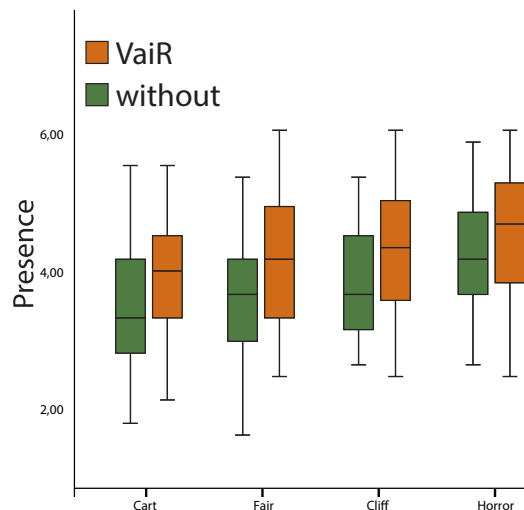**Figure 8. The results of the enjoyment scores per scene.**



**Figure 9. The results of the presence scores per scene.**

The VaiR system is placed on the participant's head. This could lead to distractions when the bows move or the nozzles (being close to the ears) be heard. We therefore compared the distractions felt by the participants when using VaiR and when not. The $E^2I$ questionnaire contains one item regarding the perceived distractions from outside VR. There could not be found any significant changes regarding the influence of VaiR on the perceived distractions (Wilcoxon signed-rank test: Z=-0.468, p>.05, mean (airflow) 2.89 vs 2.79 (no airflow)).

### Participants preferences

At the end of the session, we asked the participants to complete one last questionnaire which contained more general questions regarding the consume of VR content with or without the proposed system. Only 2 of the 24 participants stated to prefer VR without VaiR, the same participants stated that they do not want to consume VR with any simulation of airflow at all. We also asked the participants if they had in general a stronger
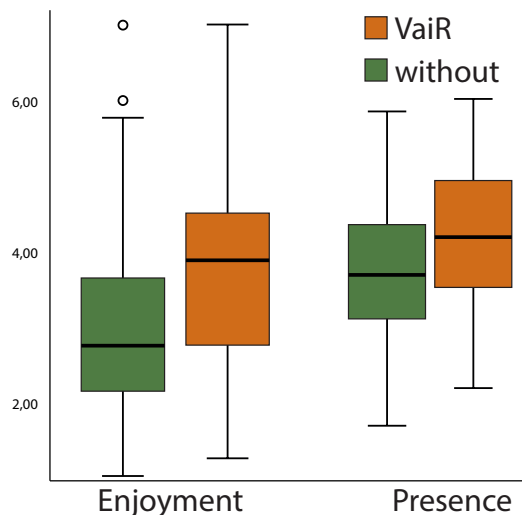
**Figure 10. The results of the $E^2I$ presence and enjoyment scores.**

feeling of being there while using VaiR, which was confirmed by all participants, except the two mentioned ones.

**Discussion**

Our results on one side confirm the results of previous works on the simulation of airflow in virtual reality to increase the felt presence. In addition, we could show that there is an even higher impact on the enjoyment while consuming VR content. We assume that enjoyment as well as presence could even influenced more in interactive gaming situations, when airflow events are related to an action.

Each scene was significantly enjoyed more when consumed with the simulation of airflow. While we could not find any significant differences between the respective scenes, except for the horror scene, presence and enjoyment increased for each scene when using VaiR. The horror scene was rated very controversial – most of all in the VaiR condition. While there was a very strong effect regarding the presence when compared to the other scenes, we could not find a significant effect for enjoyment. Since some participants stated, that the horror scene was too exciting and that the airflow simulation involved them even more in the scene (which was not perceived as positive for these participants), we assume, that the overall experience was very high in the horror scene, which was perceived as either very positive, or as negative – depending on the personal affection to horror.

Since the increase of perceived presence and enjoyment was highest in the horror and the fair scene, we assume that the fast reaction time and the possibility of simulating airflow in 3D had an high impact, since the respective scenes most of all used the named features.

Though VaiR is head-mounted and having nozzles close to the user's head, there were no additional distractions from outside VR.

Overall, 22 of the 24 participants would like to use VaiR in the context of VR, while the remaining two participants stated to prefer no airflow simulation at all.

**CONCLUSION**

In this paper we presented VaiR, a pneumatic head-mounted, mobile prototype design for the enhancement of presence and enjoyment in virtual reality (VR) by allowing precise animations of airflow in real-time. The conceptual insights of three different focus groups (including developers, users and researchers in the field of VR) were used for the design of our prototype and provided deep insights about the potential applications of airflow simulation in VR.

The developed pneumatic prototype allows the simulation of various effects, ranging from static wind over fully animated, moving object like a helicopter, to short term effects (e.g. shock wave of an explosion) in real-time. The prototype can display two independent sources simultaneously, which allows the staging VR experiences using e.g. static sources and an additional effect channel.

The insights of the focus groups, as well as some findings of related work suggest a mobile set-up. Our head-mounted system is low weighted and has a fast reaction time of under 2 ms between the raised event and the felt actuation. The two independent rotating bows additionally support mobility by not only reacting on animated airflow sources, but on user's virtual orientation.

We could confirm results of previous experiments, which showed that the treatment with wind enhances presence and could further show, that also the felt realism and most of all enjoyment is strongly influenced by airflow. Our findings strongly underline the great potential of three dimensional real-time airflow application.

We plan to further enhance the experience by the simulation of warmth by preheating the airflow and by adding olfactory cues to the air. It is also planned to test the effects in a mobile gaming scenario.

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