Wind and Warmth in Virtual Reality: Implementation and Evaluation

1st Author
1st author's affiliation
1st line of address
2nd line of address
Telephone number, incl. country code
1st author's E-mail address

2nd Author
2nd author's affiliation
1st line of address
2nd line of address
Telephone number, incl. country code
2nd E-mail

3rd Author
3rd author's affiliation
1st line of address
2nd line of address
Telephone number, incl. country code
3rd E-mail

ABSTRACT
One possibility to make virtual worlds more immersive is to address as many human senses as possible. This paper presents the development of a system for creating wind and warmth simulations in Virtual Reality (VR). Therefore, suitable hardware and an implemented software model are described. Technical evaluations of the hardware and of the software components demonstrate the usability of the system in VR Applications. Furthermore, a user study underlines users' acceptance and indicates a positive influence of wind and warmth stimuli on perceived presence.

Categories and Subject Descriptors
H.5.1 [**Information Interfaces and Presentation**]: Multimedia Information Systems – *artificial, augmented and virtual realities, evaluation/methodology*

General Terms
Design, Performance, Experimentation

Keywords
Multimodal Feedback, Wind Simulation, Warmth Simulation, Presence

1. INTRODUCTION
Due to technical advancement, virtual worlds become more and more immersive. Many systems offer realistic rendering, spatial sound and even tactile feedback like the simulation of virtual raindrops [1]. Those sensations offer the possibility of being more and more immersed in the application. Although current virtual worlds already offer a high level of realism and a set of multiple stimuli, two kinds of sensations which appear in many everyday situations are seldomly included: wind and warmth. Wind sensations proved able to enhance the users' task performance in certain areas [2] and both would also be promising extensions for VR games. Furthermore, a common type of VR applications is navigation which – in reality – includes stimuli like airflow or changes in temperature. Hence we suppose that an extension of Virtual Reality setups with wind and warmth should improve users' state of presence.

Laval Virtual VRIC '14, April 9-11, 2014, Laval, France.

Currently, no standardized hardware is available for creating such kinds of sensations in Virtual Reality and there exist only few guidelines for developing an appropriate software model. Furthermore, experimental results concerning the perception of wind and warmth sensations in Virtual Reality setups are rare. In the following, an approach to create such a system in a Virtual Reality environment is given.

The paper is organized as follows: We will start by giving an overview of related work dealing with wind and warmth in Virtual Reality and its perception in humans. The subsequent sections describe a hardware implementation and a software model for calculating and creating the appropriate stimuli. Then a technical evaluation and two user studies are presented. The contribution concludes with a discussion of the findings and a glance on future work and perspectives of this technology.

2. RELATED WORK
Presence is often described as the "sense of being there" [3]. In more detail, it refers to the degree to which a person feels rather in the virtual environment than in the laboratory used for creating the presented stimuli [4, 5]. A high level of presence allows users to solve their tasks in a more efficient way [6, 7], to reduce Simulator Sickness [8] et cetera. Among others, multimodality and the stimulation of more human senses raises the feeling of presence [9]. Hence wind and warmth simulations should be expected to contribute to the perceived state of presence. However, not much work has been reported concerning the application of wind and warmth in virtual environments. In the following section, existing approaches are discussed and results of studies concerning the perception of wind and warmth are presented.

2.1 Wind
In 2004, Moon et al. presented the WindCube: a wind simulation system for Virtual Reality applications [10]. It consists of 20 fans arranged in three levels around the user in a 1m x 2m x 1m cube. Therefore the system is able to simulate wind stimuli from nearly every direction. However, the system does not use a real time wind calculation: With an editor, a wind field must be designed manually for each scene beforehand. In a user study, the usage of wind significantly improved the presence of test subjects.

Another approach is presented by Kulkarni et al. who used the vortices of an airflow on the projection wall to adapt the direction of a presented wind up to an accuracy of 1-2° degrees [11]. However, the system can only be used with a certain display arrangement and is thus not usable for a CAVE environment. Also wind angles are only possible to be perceived in the interval [-30°, 30°]. Furthermore the wind cannot be created in realtime.

A delay of 2 to 25 seconds appears when creating certain wind directions.

Deligiannidis et al. used the "VR Scooter" for evaluating the influence of wind sensations on user performance [2]. The system is designed like a real world scooter. The user wears an HMD and navigates the scooter inside the VR. Additionally, the system comes with haptic feedback and a fan for simulating wind in front of the user. A study with 13 participants showed that the usage of wind improves task performance as well as the subjective user experience.

In addition to the above mentioned stationary systems, solutions directly mounted on the user's head are presented e.g. by Cadin et al. [12]. To evaluate the difference between systems attached to the user and stationary systems, Lehmann et al. conducted the following experiment [13]: In a ski simulation, three conditions (no wind, stationary fans, head mounted fans) were tested in a within-subjects study. The results showed a significantly higher presence when using wind. A trend indicated a higher level of presence when using the stationary wind sources.

2.2 Warmth

In 1996, José Dionisio presented a system for modeling warmth simulations for Virtual Reality applications [14]. Furthermore he described hardware devices which could be used for creating such sensations. Finally, the author proposes the use of infrared lamps and Peltier Elements for creating heat. Cooling is realized by the use of fans. In an evaluation, test subjects were able to perceive changes in stimuli in 25 percent steps. Differences concerning the position of a stimulus were perceived at a change of about 20 to 27 degrees on a circle around the test subjects.

To find thresholds concerning the perception of heat and cold, Gray et al. performed a study using Peltier Elements as stimuli source [15]. Thresholds were found at changes of a temperature raise of 1.04 degrees Celsius and a drop of 0.15 degrees Celsius: A negative change in temperature is more easily perceived than a positive change.

3. SETUP

To create a hardware and a software system with the ability to simulate wind and warmth in a Virtual Reality environment, one has to consider certain factors e.g. realtime and safety. The system presented in the following meets the requirements for wind and warmth simulations in VR, already presented in [16].

3.1 Hardware

Visual stimuli are presented in a three-sided CAVE environment (front, floor, left) equipped with 10 infrared cameras by ART. For distributed rendering and for controlling the application, the InstantReality framework developed by the Fraunhofer IGD is used. For simplifying the creation of virtual worlds, objects in a scene are enriched with information about their properties (e.g. their sound, their physical behavior). Only the type of the object must be declared and the system determines its characteristics and informs the corresponding subsystems (cf. [17]). Besides those components, the setup comprises sensations in the form of sound and tactile feedback.

3.1.1 Wind

Wind is enabled with eight axial fans by the companyADDA (see figure 1). Each of them has a diameter of 25.4 cm and a wind performance of 12.735 m^3/min. To reduce noise, the fans are driven by only 115 Volt instead of 230 Volt. The noise produced by a single fan has an intensity of 55.6 dB/A when activated with full power measured at a distance of one meter.

Figure 1: Axialfan AK25489 by ADDA.

All eight fans are attached on the top of the projection walls and are directed towards the center of the CAVE. The angle between two neighboring fans is exactly 45 degrees as proposed in the work by Moon et al. (cf. [10]). Preceding tests showed that the largest part of the wind (and also the warmth) is perceived at the head and at the hands. Therefore and because of the construction of the CAVE, all fans are placed above the user.

3.1.2 Warmth

Heat is created by using six infrared lamps (see Figure 2) as proposed by Dionisio (cf. [14]). Each has a power of 250 Watt and is able to heat the area directly in front of the lamp up to 100 degrees Celsius. To prevent a distraction of the projection by emitted visible light, heat-proof color foils are mounted in front of the lamps. Sidewards, they are surrounded by metal.

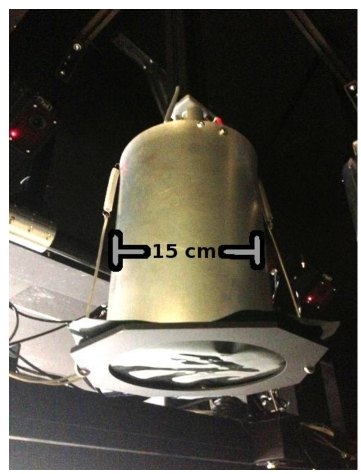

Figure 2: Infrared lamp with color foils and surrounding mounted on top of the CAVE.

The six lamps are distributed directly above the interaction area of the CAVE and they are directed towards the center. Their minimal and their maximal distance to the user can be changed according to body height to offer comparable sensations to every user. As the tracking system depends on infrared light reflections, a disturbance of the infrared based tracking system could be possible. Therefore the effect of the lamps on the tracking must be excluded or at least minimized. Measurements showed that the heat system does not reduce the tracking performance of the ART system used (cf. chapter 4.1.1).

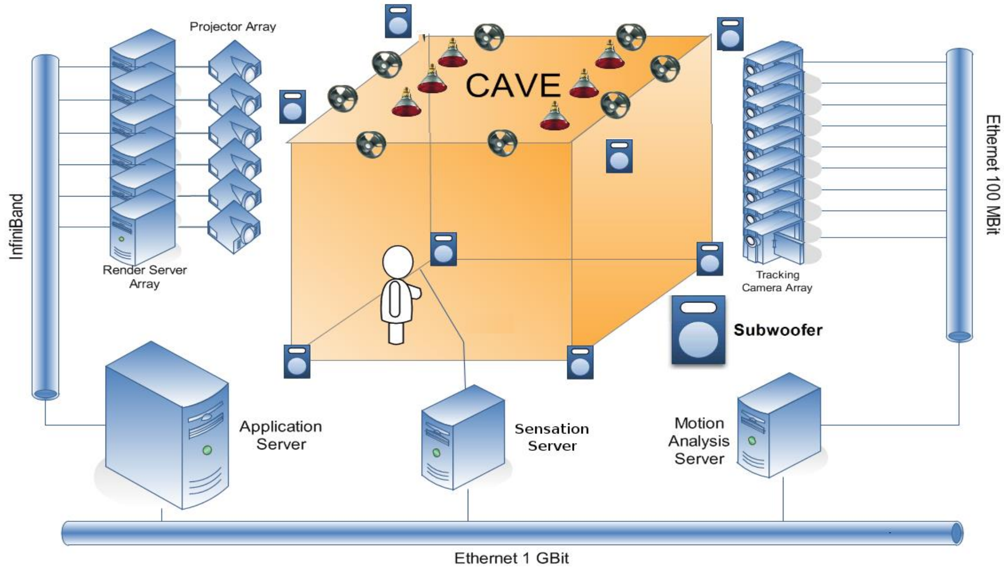

Figure 3: Technical setup containing fans and infrared lamps.

The systems temperature is monitored by two sensors. If the temperature reaches a certain threshold (45° Celsius), the system is automatically switched off. All fans and infrared lamps are controlled using MultiDim MKIII Dimmerpacks by ShowTec and are driven via the DMX protocol. Figure 3 schematically shows the setup containing the hardware for creating wind and warmth.

3.2 Software

A realistic physically modeled representation of wind and warmth sensations would be too complex to compute in realtime and with low latency. Furthermore it seems not necessary for VR applications, as other simplified models, e.g. the simulation of spatial sound, proved to be sufficient [18]. Therefore a simplified model, which resembles the use of light in Computer Graphics, is employed to approximate the influence wind and heat sources have on VR users.

3.2.1 Framework for Simulating Wind and Warmth

Inside the InstantReality scenegraph, wind and warmth sources are represented as nodes. Occlusion detection is performed within the VR Framework: Each wind and each warmth node determines autonomously whether it is occluded for the user.

All wind/warmth node changes inside the VR Framework are monitored by the system and sent to a dedicated wind and warmth engine. This engine executes all further calculations (e.g. the node's influence inside the scene, hardware activations etc.), controls the hardware and provides necessary information allowing the VR Framework to visualize wind effects. For each frame, the following calculations are performed:

1) Update all changed nodes
2) Execute calculations for wind and warmth effects
3) Activate hardware
4) Update the connected VR Framework about wind and warmth influences on the scene
5) Get information from temperature sensors for preventing overheating

Detailed algorithms to calculate occlusions and the activation of the hardware devices are presented in [16]. Figure 4 illustrates the workflow inside the whole application. The framerate of the wind and warmth engine can be manually adapted and defaults to approximately 30Hz.

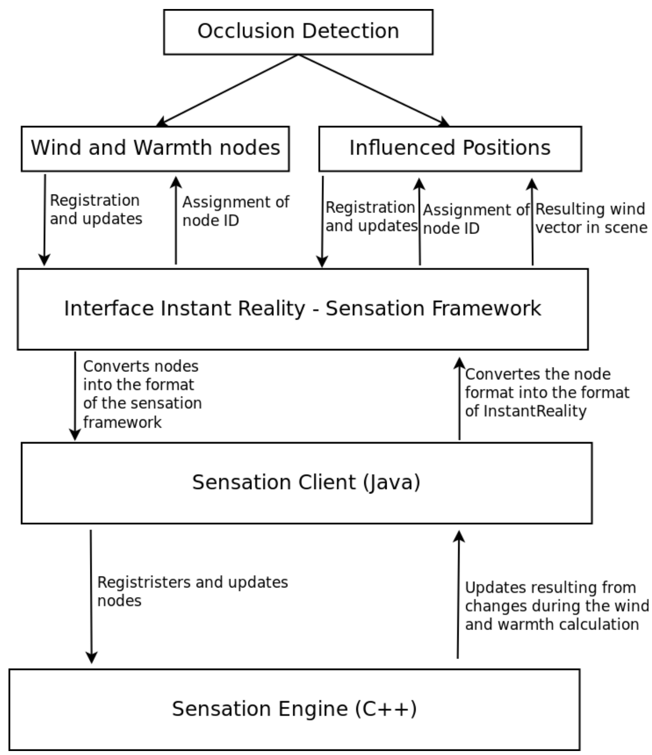

Figure 4: Workflow inside the Wind and Warmth framework.

3.2.2 Wind and Warmth Representation

The concept of virtual wind and warmth sources is inspired by the model for representing sound in Virtual Reality presented by Fröhlich and Wachsmuth [17]. To be able to manage certain types of wind and heat sources, four nodetypes have been developed: Directional Wind and Warmth, Spot Wind and Point Warmth.

Directional Wind and **Directional Warmth** are analogies to Directional Light defined in the X3D standard. The origin of the stimulus has an infinite distance to the user and its effect is thus perceivable inside the whole scene from the same direction (except from virtual occlusions). **Spot Wind** nodes have a fixed position or can be coupled to an object (e.g. a virtual fan, spray in front of a waterfall etc.) inside the scene. This kind of wind source only influences the area inside a cone directed into a given direction (see Figure 5). **Point Warmth** nodes emit their heat into all directions and have a fixed position or are bound to an object. Spot Wind and Point Warmth nodes are analogies to the Spot Light and Point Light in the X3D standard.

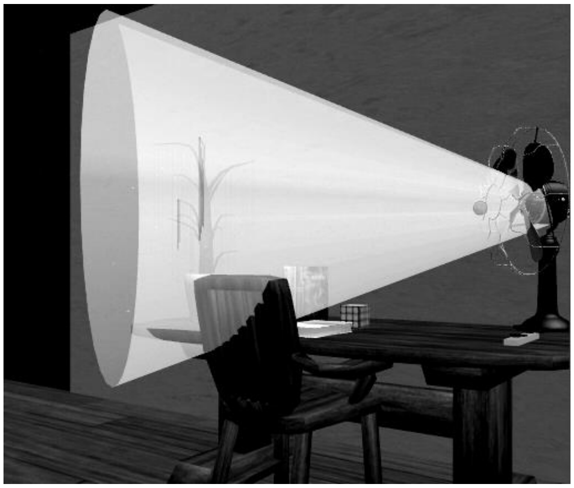

Figure 5: Visualization of Spot Wind produced by a virtual fan.

4. EVALUATION

The wind and warmth simulator was evaluated with respect to technical properties of the system and subjective user experience.

4.1 Technical Evaluation

The goals concerning the technical evaluation were to answer the following questions:

- Do the infrared heat lamps interfere with the tracking system?
- How precisely can the direction of a presented virtual wind source be estimated by test subjects?
- What is users' reaction time towards the activation and deactivation of presented wind and warmth stimuli?
- How much activation must be provided at least by the fans and the infrared lamps to make the stimulus perceivable?

4.1.1 Influence of the Infrared Lamps on Marker-Based Tracking

As already mentioned, the tracking system applied in the above mentioned setup uses infrared light. Therefore the performance of the tracking could suffer from the infrared heat lamps. To determine the influence of the infrared lamps on the size of the volume which can be tracked, a tool for measuring the coverage was developed and works as follows:

1) The volume of the CAVE is divided into 10x10x10 cuboids (approx. 0.26m x 0.208m x 0.208m).
2) A tracking target is moved manually through the CAVE. If one of the cuboids is passed at least two times by the target, it is marked as covered by the tracking.
3) The percentage of covered cuboids is returned.

First, the coverage of the original setup without activated infrared lamps is determined. Afterwards, all infrared lamps are switched on. Now, certain cameras have areas which are disturbed by the direct influence of the infrared lamps. Those areas are identified and manually excluded. Then the target is again moved through the CAVE and the coverage without infrared lamps can be compared to the coverage with lamps switched on.

The coverage of three kinds of targets was measured: An old passive target with strong signs of usage, a new passive target and an active target used for hand tracking. Table 1 shows the results.

Table 1. Comparison of the covered tracking volume for three kinds of targets.

Target type	Coverage without infrared lamps	Coverage with infrared lamps
Old passive	55%	55%
New passive	96%	96%
Active	81%	81%

In none of these tests, the infrared lamps influenced the tracked volume. Although it must be suspected that in a different setting (e.g. with fewer cameras or more infrared lamps), the lamps could affect the tracking: In those cases, too many areas in a single camera image would have to be excluded from the tracking and at some point, the coverage would suffer. Nevertheless, using enough tracking cameras, the overall quality of the tracking is not influenced by the use of infrared lamps.

4.1.2 Wind Direction, Reaction Times and Activation Thresholds

To determine wind direction, reaction times and activation thresholds, a study with N = 9 test subjects from the age of 20 to 51 years (M = 22.67, SD = 10.3) was conducted. Participants were recruited through postings in the university building. All of them were native speakers of German. Most of them were students at Bielefeld University. In total 32 percent were female. First, the estimation of presented wind directions was tested, afterwards reaction times and activation thresholds were measured.

4.1.2.1 Setup

A participant is located in the center of the CAVE and holds a Nintendo Wii Remote equipped with a tracking target in the dominant hand. In the first step of the experiment, the participant's accuracy concerning the pointing with the Wii Remote is measured. A single blue circle is projected on one of the CAVE screens. The participant uses the Wii Remote to point at the circle and presses a button. The dot vanishes and appears at another position. This procedure is repeated eight times. Afterwards, the pointing error (in degrees) with respect to the x and z axis is saved. Then, the participant is blindfolded. Instead of visual stimuli, the system now presents wind stimuli. The participant uses the Wii Remote to point into the direction of the stimulus. Then a button is pressed. The wind is stopped and another wind source is presented. This procedure is again repeated eight times. The error with respect to x and z axis is saved. The y axis is excluded, because the fans are only mounted in one height and are thus unable to simulate any changes on the y axis. The possible positions of the wind sources are varied between participants using a 9 x 9 Latin square pattern.

In a second step, a wind source which lies directly in front of the participant is switched on with full power. As soon as the participant perceives the stimulus, a button has to be pressed on the Wii Remote. The stimulus is then presented for a few more seconds. After perceiving that the stimulus has stopped, the button has to be pressed again. The same procedure is repeated using heat from the infrared lamps instead of wind. All six lamps are used with full power.

Finally, the fans are activated in five percent steps until the participant perceives the stimulus and presses the button. This is repeated using the infrared lamps afterwards.

To prevent giving hints on the wind's direction or activation time due to the fans' noise, wind sounds are presented during all parts of the experiment when the participant is expected to sense wind. Those sounds come from all directions, so that the hearing cannot be used to gain any information.

4.1.2.2 Procedure

After participants filled in a consent form, they are accompanied to the CAVE. Here, demographic data is collected and the participants are instructed. They are placed inside the CAVE and equipped with tracked 3D goggles and the Nintendo Wii Remote. After pointing on the blue circles, the investigator explains the following test and blindfolds the participants. After pointing towards all wind sources, the participants are instructed for the next part of the experiment: pressing a button as soon as they feel the appearance or disappearance of wind and warmth stimuli. Finally, their blindfold is taken off and the participants are thanked for participating. The whole experiment needs approximately 10 minutes.

4.1.2.3 Results and Discussion

Overall, results show that the wind direction is detected with an accuracy of M = 24.13 degrees (SD = 30.25). After subtracting the mean error for pointing with the Wii Remote, the resulting accuracy is at about 14.13 degrees. Figure 6 visualizes the accuracy and its standard derivation.

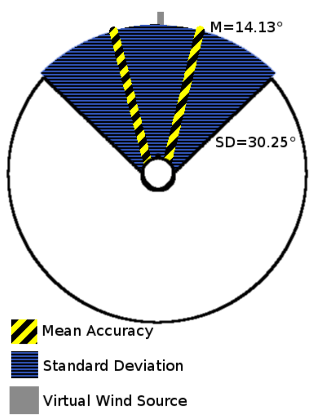

Figure 6: Accuracy concerning the detection of the wind direction. The small white circle visualizes the user.

Concerning the reaction times towards activated and deactivated wind and heat sources, it is eye-catching that the time for perceiving a new stimulus is longer than the time for perceiving the disappearance of a stimulus (Wind: $M^+ = 3.1s$ and $M^- = 1.3s$, Warmth: $M^+ = 2.5s$ and $M^- = 2.0s$). Concerning wind, the analysis of variance reports a high significance ($p < 0.01$) for this finding (cf. table 2).

Table 2. Reaction time towards activation and deactivation of wind and heat sources.

Reaction time	Time in seconds Mean (Standard Deviation)
Fans on	3.144 (0.290)
Fans off	1.313 (0.850)
Lamps on	2.450 (1.933)
Lamps off	2.045 (2.081)

To perceive warmth, the infrared lamps have to be activated with about M = 57 (SD = 21) percent. To perceive wind, an activation of M = 47 (SD = 9) percent is sufficient. These results must be considered when developing applications using the present system. Furthermore, the high values suggest the use of stronger hardware devices to provide a more intense feeling.

The measured results are adequate to use the presented system in Virtual Reality applications. Although the response time towards the wind and warmth stimuli seems to be quite long at the first glance, the evaluation of subjective factors shows that the system is able to create realistic impressions in possible users. One reason could be the combination with visual stimuli in the conducted user study described in the following.

4.2 Subjective Factors

In a further study, the following properties of the system were investigated:

- Realism of the direction of wind and warmth
- Realism of the intensity of wind and warmth
- Influence of wind and warmth on users' presence

To measure these properties, we conducted a study with 23 participants (9 female, 14 male; $M^{age} = 25$, $SD^{age} = 8.68$). They were recruited through postings in the university building. Participants were randomly assigned to one of two between-subject conditions: One group perceived wind and warmth stimuli, the other group did not.

4.2.1 Setup

A participant is placed at the center of the CAVE and holds a tracked Nintendo Wii Remote. An information text is projected and describes the participant's fictitious role in the following experiment: "As a researcher on an expedition you will move through certain different environments. During the experiment, you have to solve small tasks".

Subsequently, another text is presented. It contains a short introduction to the following virtual world and instructs the participant to closely investigate and remember the environment. Now the first scene is presented. To prevent to overcharge the participant with learning special navigation techniques, the participant is moved automatically through the environment. The only direct interaction with the scene consists of virtual buttons which can be activated by the participant using the Wii Remote. After moving through the scene, a questionnaire is filled out. This procedure is repeated with five different scenes. To prevent an influence on the results according to the order in which the scenes are presented, they are varied using a 5x5 Latin Square pattern. Each scene contains wind and/or warmth stimuli. The following list presents the scenes used (cf. figure 7):

- **1: Desert (Warmth)**: The participant is inside a room with a gate at one side. It can be opened by activating a virtual button. After passing the gate, the participant is moved through a sparse desert-like environment. As soon as the participant enters the desert, a warmth stimulus is presented.
- **2: Volcano (Wind and Warmth)**: The participant is placed on a scaffold over an ocean. The scaffold leads to an isle with a volcano. At first, the participant perceives a wind stimulus. When approaching the volcano's lava lake, the wind is occluded and a warmth stimulus is presented.
- **3: Fan (Wind)**: A living room is crossed by the participant. From the right, a wind stimulus can be perceived. It results from a virtual fan, which is placed on a desk. The participant can control the fan's intensity by using virtual buttons on the desk.
- **4: Chimney (Warmth)**: In a small room, a virtual chimney is presented. First, it is covered by a transparent pane. The participant can remove the pane by pressing a virtual button. This intensifies the presented warmth stimulus.
- **5: Train (Wind)**: The participant moves through a railway tunnel. After a time, sounds created by an approaching train can be perceived. The navigation speed is increased and just before the train arrives, the participant is stopped and placed next to the tunnel's wall. When passing the participant, the train produces wind.

4.2.2 Measures
All depending variables were measured using five types of questionnaires:

1. A questionnaire asking for demographic information.
2. Immersion Tendency Questionnaire (ITQ). This questionnaire was first presented by Witmer and Singer in 1998 [19]. It consists of 12 questions to measure the capability of individuals to get immersed in everyday activities (e.g. reading, watching a movie etc.).
3. Simulator Sickness Questionnaire [20]. This questionnaire measures the influence of the simulation on the participants' health.
4. Modified version of the Slater, Usoh, Steed Questionnaire (SUS) [21] to determine the participants' presence.
5. A questionnaire adapted to the scenes to determine the quality of the stimuli's direction and intensity and further open questions about participants' experience. Participants also had the chance to write a short text about how they liked the experiment and if there were any suggestions for improvements.

Questionnaires which were originally presented in English, were substituted by a reevaluated German version.

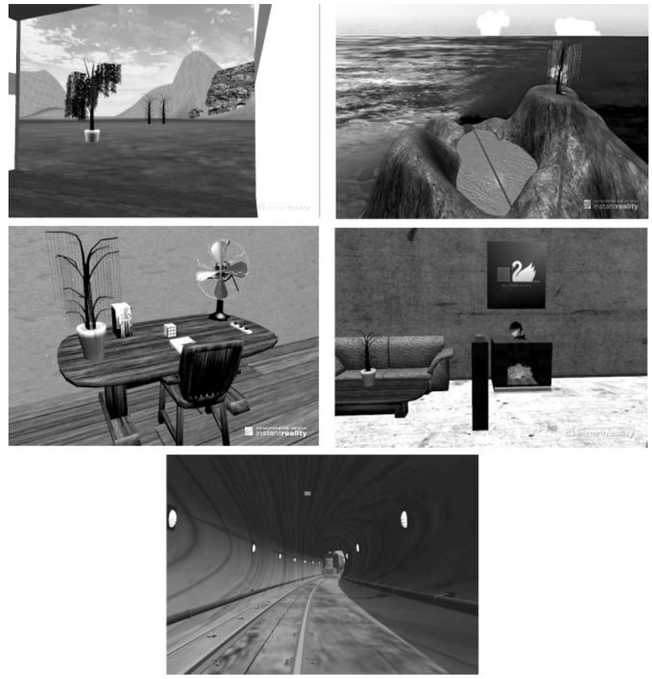

Figure 7: Scenes presented for the subjective measures. From left to right and top to bottom: Desert, Volcano, Fan, Chimney and Train.

4.2.3 Procedure
Before entering the virtual environment, the participants have to fill out a consent form and the questionnaires 1, 2 and 3. Then, the participants are placed in the center of the CAVE and equipped with a Wii Remote and tracked goggles. After explaining the procedure, the information text is presented on the projection walls. Next, each scene is presented and followed by questionnaire 4 and 5. After encountering all five scenes, the Simulator Sickness Questionnaire is answered again. Eventually, the participants are thanked for joining the experiment. This procedure needs approximately 30 minutes.

4.2.4 Results and Discussion
According to the results, the Immersion Tendency as measured by the ITQ is balanced between the control group and the group perceiving wind and warmth stimuli ($M^{control} = 31$, $SD^{control} = 11$, $M^{ww} = 36$, $SD^{ww} = 11$). In the following, the results are presented separated into results concerning the realism of presented stimuli and results concerning the presence reached by using wind and warmth.

4.2.4.1 Realism of the Stimuli
The realism of the intensity is rated on a scale in the interval [-2, +2]. The optimal value is 0. A value of -2 means that the stimulus is too weak, a value of +2 indicates a stimulus which is perceived as being too strong. Figure 8 illustrates the detected results for the quality of the stimuli's intensity.

Concerning the realism of the direction, the optimal value is 0 on a 5 point scale in the interval [0, 4]. A value of 4 means that the direction is completely unrealistic. Figure 9 shows the results of the quality of the stimuli's direction.

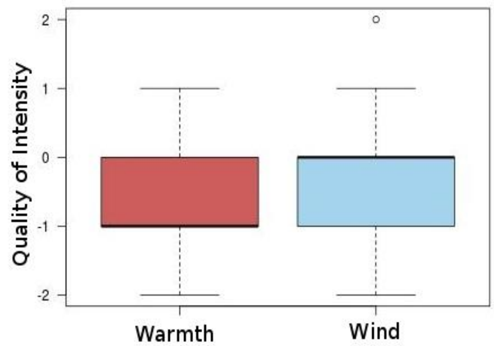

Figure 8: Quality of the perceived stimulus intensity.

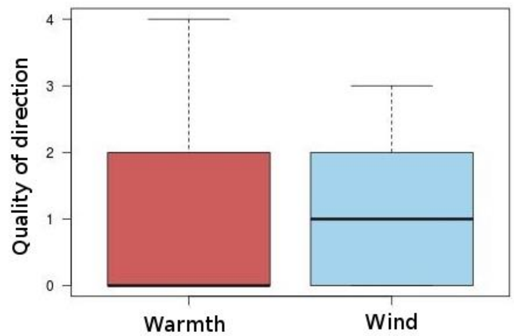

Figure 9: Quality of the perceived stimulus direction.

Wind is perceived as being realistic concerning both, intensity (M = -0.39, SD = 1.01) and direction (M = 1, SD = 1.16). A closer look on the results for the single scenes (cf. table 3), points out some differences depending on the scene which was encountered. In scene 3 (Fan), the intensity was reported as being significantly stronger than in the other scenes using wind ($p < 0.05$). Concerning the direction, the ANOVA shows no significant results (p = 0.115). Nevertheless the participants reported the composition of the scene as being irritating, especially because of the positioning of the fan.

Table 3. Realism of wind intensity (0: optimal, -2: too weak, +2: too strong) and wind direction (0: optimal) for the single scenes. Codes of significance: ** p < 0.01 * p < 0.05

Mean (Standard Deviation)	Intensity	Direction
Scene 2: Volcano	-0.727 (0.8)	0.545 (0.8)
Scene 3: Fan	0.273 * (1.0)	1.545 (1.2)
Scene 5: Train	-0.727 (0.9)	0.909 (1.2)

Warmth in general is perceived as being a little too weak, but sufficient (M = -0.73, SD = 0.85). Concerning the direction of the stimuli, the results are satisfying as well (M = 0.88, SD = 1.34).

Looking closer at the single scenes (cf. table 4), scene 4 (Chimney) has the weakest results concerning the intensity. This difference is not significant but can be seen as a trend (p = 0.0618). A possible reason could be the fact that the lamps' activation was during maximal activation at about 60 to 70 percent, which is quite near the lower threshold for perceiving warmth (see chapter 4.1.2.3).

Concerning the direction, the results for scene 1 (desert) are slightly better than for the other scenes ($M^{desert} = 0.545$, $M^{chimney} = 1.0$, $M^{volcano} = 1.1$). A reason could be the fire's position: The visual stimulus (visualization of the fire) comes from below, whereas the haptic stimulus comes from above (due to the placement of the lamps). Indeed, these results are not statistically significant. Therefore, further investigations concerning the importance of a match of the direction of visual and wind/warmth stimuli will be carried out.

Table 4. Realism of warmth intensity (0: optimal, -2: too weak, +2: too strong) and warmth direction (0: optimal) for the single scenes. Codes of significance: .. p < 0.1

Mean (Standard Deviation)	Intensity	Direction
Scene 1: Desert	-0.364 (0.8)	0.545 (1.3)
Scene 2: Volcano	-0.636 (0.8)	1.1 (1.4)
Scene 4: Chimney	-1.182 .. (0.75)	1.0 (1.4)

4.2.4.2 Presence

According to Usoh et al., the number of high answers (top 3 on the 7 point Likert scale) of the questions in the SUS questionnaire is used for determining the perceived presence [21]. Hence the overall score is rated in the interval [0, 7]. Figure 10 shows the mean for each scene divided into both groups: Those participants who perceived wind and warmth and those who did not.

For most scenes, no significant differences between both conditions were found. This could be due to the short scenes: Maybe, the participants did not have enough time to let themselves immerse in the virtual world. This hypothesis is supported by some comments of the participants after the experiment. Also the overall number of participants could have been too small. Nevertheless, two scenes indicate a higher presence when using wind and warmth: A statistical trend can be found for scene 1 (Desert) and for scene 2 (Volcano) with $p^{desert} = 0.086$ and $p^{volcano} = 0.13$. Further studies with more participants and additional measures e.g. heart rate or skin conductance are desirable.

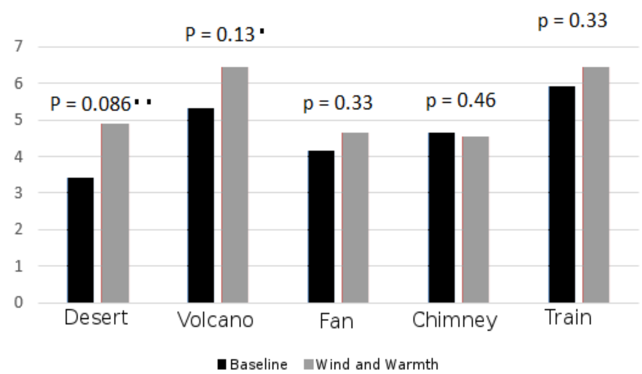

Figure 10: Subjective measured presence. Codes of significance: ** p < 0.01 * p < 0.05 .. p < 0.1 . p < 0.15

5. CONCLUSION

This paper described a setup able to create realistic wind and warmth stimuli for the application in VR. The whole system was evaluated in a technical study and a study investigating subjective measures. The new hardware neither disturbs the existing setup, nor the users' experience. The results rather suggest that the system satisfies the requirements for the use in the Virtual Reality context and is accepted by the participants. Furthermore the results concerning the perceived presence show that the addition of wind and warmth as modalities in VR is able to increase the users' presence.

5.1 Future Work

The presented system is – to our knowledge – one of the most extensive, most flexible and best evaluated developed system for creating wind and warmth stimuli in Virtual Reality applications designed for CAVE environments. Although the system's capabilities are satisfactory and the reported results are promising, there is a large potential for possible extensions. Virtual occlusions are handled quite rudimental: A stimulus is occluded or it is not. But what about for example the difference between a fire which is occluded by a thick concrete wall and a fire which is occluded simply by a pane of glass? To be able to simulate those situations, materials must be equipped with a kind of wind-/warmth transparency factor alpha. To handle the occlusions itself, algorithms well known from the area of computer graphics (e.g. shadowing) could be used. Concerning possible evaluations, a determination of crossmodal influences between wind and warmth stimuli which are presented at the same time would be interesting. Also the quality of the presented stimuli with respect to the user's position inside the CAVE should be analyzed: How much do the sensations damp due to a user standing next to a wall and are there any turbulences when a fan blows onto a wall? In a large user study, the influence of wind and warmth on the users' presence will be analyzed in detail. Here, especially the importance of the accuracy of the presented directions and the finding of appropriate intensities will be focused. Another important question is how far the setup is comparable with head mounted solutions (e.g. [CTV07]).

These future findings together with the system presented here will lead to a detailed guidance for creating wind and warmth stimuli in Virtual Reality applications. In the future, a precise advancement of the findings could make wind and temperature modalities as self-evident in Virtual Reality as sound is today.

6. ACKNOWLEDGMENTS

The authors would like to thank hidden name for his technical work in preparing our previous approach to the wind system.

7. REFERENCES

[1] Hoshi, T., Takayuki, M., Nakatsuma, K. and Shinoda, H. 2009. Touchable holography. *ACM SIGGRAPH 2009 Emerging Technologies*, 23.

[2] Deligiannidis, L. and Robert, J.K. 2006. The VR Scooter: Wind and Tactile Feedback Improve User Performance. *3D User Interfaces (3DUI'06),* 143-150.

[3] Slater, M., Usoh, M. and Steed, A. 1995. Taking steps: The influence of a walking technique on presence in virtual reality. *ACM Transactions on Computer-Human Interaction (TOCHI).* 2, 3, 201-219.

[4] Bystrom, K., Barfield, W. and Hendrix, C. 1999. A Conceptual Model of the Sense of Presence in Virtual Environments. *Presence: Teleoperators and Virtual Environments* 8, 2, 241-244.

[5] Ijsselsteijn, W., de Ridder, H., Freeman, J., and Avons, S. 2000. Presence: Concept, Determinants and Measurement. *Electronic Imaging. International Society for Optics and Photonics*, 520-529.

[6] Pausch, R., Proffitt, D., and Williams, G. 1997. Quantifying immersion in virtual reality. *Proceedings of the 24th annual conference on computer graphics and interactive techniques*, 13-18.

[7] Usoh, M. and Slater, M. 1995. An exploration of immersive virtual environments. *Endeavour* 19, 1, 34-38.

[8] Taylor, W. 1997. Student responses to their immersion in a virtual environment. *ERIC Clearinghouse.*

[9] Dinh, H. Q., Walker, N., Hodges, L.F., Song, C., and Kobayashi, A. 1999. Evaluating the importance of multi-sensory input on memory and the sense of presence in virtual environments. *Virtual Reality, 1999. Proceedings., IEEE*, 222-228

[10] Moon, T. and Kim, G.J. 2004. Design and evaluation of a wind display for virtual reality. *Proceedings of the ACM symposium on Virtual reality software and technology*, 122-128.

[11] Kulkarni, S. D., Minor, M. A., Deaver, M. W., Pardyjak, E. R. and Hollerbach, J. M. 2012. Design, sensing, and control of a scaled wind tunnel for atmospheric display. *Mechatronics, IEEE/ASME Transactions on,* 17, 4, 635-645.

[12] Cardin, S., Vexo, F., and Thalmann, D. 2007. Head mounted wind. *Computer Animation and Social Agents (CASA2007),* 101-108.

[13] Lehmann, A., Geiger, C., Woldecke, B., and Stocklein, J. 2009. Poster: Design and evaluation of 3D content with wind output. *3D User Interfaces, 3DUI 2009, IEEE Symposium on.*, 151-152.

[14] Dionisio, D., 1996. Temperature feedback in Virtual Environments. *Imaging Sciences and Display Technologies*, 233-243.

[15] Gray, L., Stevens, J. C., Marks, L.E. 1982. Thermal stimulus thresholds: Sources of variability. *Physiology & Behavior* 29, 2, 355-360.

[16] Hülsmann, F., Mattar, N., Fröhlich, J., and Wachsmuth, I. 2013. Wind and Warmth in Virtual Reality – Requirements and Chances. *Proceedings of the Workshop Virtuelle & Erweiterte Realität 2013*, 133-144.

[17] Fröhlich, J. and Wachsmuth, I. 2012. Acoustically enriched virtual worlds with minimum effort. *Virtual Reality Workshops (VR), 2012 IEEE*, 147-148.

[18] Fröhlich, J. and Wachsmuth, I. 2013. The Visual, the Auditory and the Haptic – A User Study on Combining Modalities in Virtual Worlds. *Virtual, Augmented and Mixed Reality, Part I, HCI 2013*, 159-168.

[19] Wittmer, B. G. and Singer, M. J. 1998. Measuring presence in virtual environments: A presence questionnaire. *Presence: Teleoperators and virtual environments* 7, 3, 225-240.

[20] Kennedy, R. S., Lane, N. E., Berbaum, K. S., and Lilienthal, M. G. 1993. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology* 3, 3, 203-220.

[21] Usoh, M., Catena, E., Arman, S., and Slater, M. 2000. Using presence questionnaires in reality. *Presence: Teleoperators and Virtual Environments* 9, 5, 497-503.