A Somatic Approach to Combating Cybersickness Utilising Airflow Feedback

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Abstract

This paper presents a novel somatosensory approach towards reducing the risk of cybersickness during virtual reality locomotion in a 3D environment. We start by presenting theories regarding the cause of cybersickness which led to the proposal and construction of a prototype airflow-based feedback system. The solution proposed by this paper builds on the concept of sensory misalignment, where the body struggles understand its state due to conflicting sensory feedback and consequently generates negative health symptoms and discomfort. To evaluate the work an experiment was carried out where 40 participants drive a simulated car around a virtual environment. In one condition the participants had additional somatosensory feedback regarding their motion, provided by a fan synchronised to their speed in the virtual world. In the second condition there was no additional feedback. We evaluated both conditions for cybersickness and presence, and showed a statistically significant improvement for both in the condition using airflow feedback. We conclude with a discussion of the results, and present a direction for possible future research.

CCS Concepts
• Human-centered computing → Virtual reality; • Software and its engineering → Interactive games;

1. Introduction

Virtual reality sickness, or 'cybersickness' is a considerable obstacle in the development and commercialisation of Virtual Reality (VR) experiences and research. Specifically, experiences which involve the movement of a player within a virtual environment (VE) can be rendered unplayable due to discomfort. This significantly limits the scope of activities that can be engaged with, which may be an issue for virtual reality games. As the games industry is moving towards fully-immersed gaming in VR [HJW*16], this is a prominent issue which may affect progress. Furthermore, using virtual reality for extended periods increases the likelihood of cybersickness symptoms, restricting users to short, infrequent play sessions to avoid discomfort. The scope of VR applications would broaden considerably if a method of reducing cybersickness is devised, as player movement in virtual environments could be experienced without discomfort.

Currently, most research only offers solutions which involve the inclusion of additional equipment in VR configurations. In standing VR configurations, omnidirectional treadmills can be used to emulate vestibular feedback expected from walking [Ocu16]. Similarly, motion simulators can be used in desk-based setups to imitate the forces experienced through movement. However, the expensive price of these solutions makes them largely inaccessible to the typical consumer.

The somatosensory system is one of three significant contributors to the central nervous system, which is responsible for the body's management of balance and posture [FNIM01]. Existing research shows that somatosensory feedback influences cybersickness, and symptoms can be reduced through haptic feedback [LVJ*04]. However, this area remains mostly unexplored, despite its significance in VR research. We believe that this evidence, along with the lack of attention in this area, warrants a more detailed investigation into the role of somatosensory feedback on cybersickness. This paper aims to explore this topic.

A potentially beneficial byproduct of additional sensory feedback is an improved sense of immersion and presence within VR, amongst users. We also additionally aim to investigate how somatosensory feedback affects user presence within VR applications.

2. Background

Cybersickness is a form of nausea that some users feel following or during a VR experience. It is symptomatically comparable to Motion Sickness, and similar theories have been used to explain its effects. Motion Sickness has a wide variety of reported symptoms but is typically associated with nausea and vomiting. Reason [Rea78] examines the causal effect of motion sickness by investigating the *sensory rearrangement theory*. This theory proposes two hypotheses. The first is that visual, vestibular and non-vestibular proprioceptive systems all receive stimulus, however these stimuli are at

variance with one another and consequently with what is expected of the actions in the environment [RB75]. The second, is that the vestibular system must be involved for motion sickness to occur, regardless of other sensory systems. As a result, Reason identifies that effective motion stimulus must involve a changing velocity component, since vestibular receptors are only responsive to angular and linear accelerations.

One criticism of this theory is the lack of explanation as to why a sensory difference can make someone sick [LaV00]. Treisman [Tre77] attempts to address this in his work. The premise is that the cause is not a difference in the present sensory input and past experience, but in the occurrence of a scenario where two associated spatial reference undergo unpredictable perturbations to the previous established correlation. It is theorised that nausea occurs due to the body's reaction to this disturbance, incorrectly assuming it is symptomatic of ingested toxins.

Cybersickness is often assumed to be the same as motion sickness due to the similarities in their symptoms. However, LaViola Jr clarifies that for the former, vestibular motion alone can be enough to prompt motion sickness, although visual factors can also contribute [LaV00]. With cybersickness, visual stimulation without vestibular motion is the most common reason for its occurrence, however as motion sickness cannot occur in static environments [Bos07] many researchers believe they are separate (but related) conditions.

2.1. Theories of Cybersickness

The cause of cybersickness is still unknown, and the majority of the underlying physiological reactions are unclear. However, there are three leading theories surrounding what causes cybersickness; the sensory conflict theory, the poison theory, and the postural instability theory.

The sensory conflict theory is the most commonly accepted theory, and centres around discrepancies between the vestibular and visual sensory systems. Information about an individual's orientation and perceived motion is provided by these systems. However, it has been shown that virtual reality can cause a disagreement between the two [DNN14]. Some issues surrounding this theory include why the body cannot process the information and why some individuals are affected by it more frequently or severely than others, despite given identical stimuli [LaV00].

A second theory of cybersickness is the postural instability theory, originally presented by Riccio and Stoffregen [RS91]. The theory suggests that prolonged instability and lack of control accumulates from a variety of factors such as low-frequency vibration, weightlessness, changing relationships regarding the gravitoinertial forces, and altered specificity.

Cybersickness is classified as altered specificity, due to the optically specified accelerations and rotations that are unrelated to the constraints on control of the body. Postural control strategies such as using muscular force to resist to the acceleration interpreted visually will have no impact, creating a subconscious diversion from a stable position. This occurring repeatedly on a subconscious and micro level has been found to cause sickness. The postural instability theory however lacks validation, and falls into the same pitfalls as the sensory conflict theory, accounting for the existence of symptoms but not their nature [RS91]. However, the postural instability theory does have more predictive power than than other theories [MDS17].

The poison theory is another leading theory regarding the manifestation of cybersickness [Mon90]. In some scenarios, the nature of the visual stimulation combined with a lack of vestibular feedback can be misinterpreted by the nervous system as a form of hallucination [DNN14]. In this situation, an emetic response may occur as the body attempts to remove the hallucinogenic or sense impairing toxin from the body [LaV00]. However, it fails to explain the volatility of reactions among participants given identical stimuli.

2.2. Contributing Factors to Cybersickness

Outside of the primary cybersickness theories, a significant number of additional contributing factors have been noted over the history of VR. In this section we briefly review a some of these factors. For a more exhaustive review of these factors, see [BL17; SMK98; Kol95].

Optical flow is believed to be the primary contributor to the illusory sensation of vection. Vection is the false sensation of self-motion and can be induced by viewing representations of motion in any of the linear or rotational axes of the body. The optical flow rate also alters the induction of vection, since a faster flow rate will increase the perceived speed, thus making the sensation more pronounced [LaV00]. The most common real-life example of vection occurs as a train passenger, where seeing the movement of an adjacent train creates the sensation that one's own stationary train is moving [KRHC15].

In standard perception of self-motion, the spatial components visualised would be accompanied by vestibular information. However, in the majority of virtual reality configurations, vestibular cues are not present [KHL90]. In the case of virtual reality games, this is especially important considering the frequency of visually-perceived movement within a virtual environment. As a result, a number of virtual reality games bypass this issue by utilising alternative movement modalities, such as teleportation [AH18].

Flicker is the perceived inconsistency when viewing a display, in which the visibility of visual output changes at a high frequency. Not only is this distracting to users, it cause eye fatigue and contribute to the induction of cybersickness symptoms [LaV00]. Latency or lag describes the time between a user initiating an action and the action occurring in the virtual environment [LaV00]. A common example of lag in VR is head movement being delayed, due to issues with head tracking. If there is a high amount of latency in a system, the visual display will be delayed in updating between actions, breaking user immersion. This provides an unsettling experience, and is also a cause of cybersickness symptoms. While there are many variants of lag [Wlo95], they largely share the same solution of high processing power, supported by software efficiency and quality systems [ZWB*17]. Issues around calibration may also have an impact on cybersickness [MS92] as correct size, accurate focus and correct alignment can reduce

the possibility or effect of cybersickness [BBP09]. Modern head-mounted displays (HMDs) accommodate these factors by using adjustable straps as well as means to adjust the interpupillary distance of lenses, such that it meets the dimensions of almost any user.

Field of view (FoV) is the extent of the world that is seen at any given moment, measured as an arc on an axis. For example, humans have a stationary forward facing horizontal arc of $180°$, and a vertical arc of about $150°$. Both the Oculus and Vive VR headsets utilize a $110°$ horizontal arc, which is partially due to limitations of lens technology, but also a development to combat cybersickness. Line et al. [LDP*02] presents findings suggesting a positive correlation between sickness and increasing FoV, up to a horizontal arc of $140°$, where further changes begin to have negligible impact. They also found that higher FoV correlates to greater presence within the virtual environment, which often correlates to positive immersion and engagement [WS98]. The $110°$ FoV that has recently become standard could be seen as a middle ground between presence and sickness risk. FoV also plays a critical part in the induction and strength of vection sensations due to a large FoV stimulating more of the retinal periphery [KHL90], consequently increasing the likelihood of encountering discomfort due to cybersickness [vEdVB11].

2.3. Airflow as Feedback

The majority of existing cybersickness research has overlooked somatosensory feedback as it does not directly contribute to the sensory conflict theory. However, from a physiological perspective, the somatosensory nerve system is one of the three significant contributors to the central nervous system. Alongside the vestibular and visual systems, it is responsible for the body's management of balance and posture [FNIM01]. A study by Gaerlen et al. [GAC*12] investigating the balance and posture of young adults found that the visual system was used predominantly to determine balance with other systems acting secondarily. While this might suggest that visual elements should be the focus of improvement for VR, the authors include that the dominant system can change depending on the strength of each system in a given scenario, such that when blindfolded other systems become dominant. While VR is not complete vision impairment, it restricts the visual system, such that by supplementing other sensory systems the body will be more capable of utilizing them. However, while existing research has already found that somatosensory stimuli does not invoke motion sickness [Bos07], additional research is required to determine any positive beneficial effects.

Airflow or wind in VR currently has fairly minimal research coverage. One example is in the work of Moon and Kim [MK04], in which the authors use a wind display system called the 'WindCube' with the aim of enhancing presence. Building on this, later work has shown that airflow can significantly influence a user's sense of presence [RPK*17; KIS*18]. Using similar airflow could provide additional sensory feedback to the somatosensory system, possibly reducing motion sickness. However, research considering the use of airflow to reduce motion sickness is significantly limited.

To our knowledge, the only paper concerning this topic is by

D'Amour et al. [DBK17], who found that airflow dramatically reduced the visually-induced motion sickness (VIMS) of participants, during a passive video experience. However, the applicability of airflow to reduce motion sickness in virtual reality settings was not considered by the authors. Furthermore, the video shown was of a low quality, and involved no user interaction. We intend to expand on this by a) observing if this is the case with immersive VR head-mounted displays, at a higher resolution and b) consider if this is the case within interactive virtual reality games.

3. Design

A prototype airflow feedback system was developed to explore whether somatosensory feedback could have a positive impact in Virtual Reality. This prototype consisted of virtual reality driving game, in which the player uses a steering wheel/pedals as a control mechanism. In particular, the Oculus Rift (with integrated headphones) and the Trust GXT 570 wheel/pedalset were used.

The prototype also consisted of a standard 15" desk fan, whose purpose was a method of providing somatic feedback to the player. The fan consisted of four discrete speed settings, ranging from low to high speeds. This was unsuitable for the needs of the experiment, as we wished to simulate a continuous range of airflow speeds. A dial-operated variable power controller was used to circumvent this issue, allowing seamless and variable control of the fan's RPM.

An Arduino Mega 2560 R3 micro-controller was used to enable communication between the virtual reality game and the fan system via a 5V servomotor, attached to the variable speed dial. This allowed for fan speeds to be set whilst the game plays. The game was then developed to send data to the Arduino, synchronising the speed of the fan with the speed of the in-game vehicle. This allowed the player to experience airflow consistent with their speed in Virtual Reality. It is also worth noting that the limits of the variable speed controller were normalised against the maximum speed of the in-game vehicle.

Figure 1: *An in-game screenshot of the game used within this experiment.*

The virtual reality game was purpose-built for this experiment, using the Unity 3D engine. The Unity 3D engine was used as it allows for rapid development, whilst also providing functionality for easily connecting the airflow feedback system to the game. The VR game consisted of a vehicle which could be freely driven by participants within a virtual environment. The steering wheel and

pedalset were provided as an interaction method to directly control the in-game vehicle.

Figure 2: *An image of the steering wheel and head-mounted display used throughout the experiment.*

The task assigned to participants consisted of two VR exposures, separated with data completion and a short break. For each exposure, participants wore the Oculus VR headset and were placed into the virtual environment in a simulated vehicle, where they were asked to drive around the environment following large way-point markers. Participants were informed at the start of the study that their task performance is not being assessed in a competitive sense.

In the experiment, participants drove two times in five minute exposures, for a total time of ten minutes. Participants were assigned randomly to an initial group, with a 50% split between the two groups (20 participants in each). These groups determined in which order somatosensory feedback would be applied throughout the two driving exposures. In the first group, somatosensory feedback was enabled in the first exposure, and disabled in the second. Conversely, the second group did not receive somatosensory feedback in the first exposure, but did in the second. This type of counterbalancing was used to control order effects in the experiment.

4. Method

4.1. Hypothesis

Our hypothesis for this experiment is that the frequency and severity of cybersickness symptoms will reduce with the inclusion of somatosensory feedback, in line with previous work [DBK17]. Furthermore, with previous research considered [MK04; KIS*18; RPK*17] we would expect to see an additional improvement in user presence.

4.2. Participants

The study was started with 40 participants who passed a screening process, excluding individuals who were significantly at-risk (such as participants who were pregnant). Of the 40 volunteering participants, 38 completed the study, 29 males and 9 females. Two male participants chose not to complete the study after experiencing overwhelming sickness symptoms in their first exposure. The participant base had an age range of 19 to 28 (mean = 22.18, median = 22). All participants were undergraduate or postgraduate students from the University of Lincoln. There was no additional incentive included with the study. Participants also filled out a brief form ascertaining some basic information, their age, sex, and previous VR experience, allowing for the assessment of the participant demographic and for potential examination of correlations between participant information, and measured values. It is also worth noting that the purpose of the study was not discussed with participants, to eliminate any predisposition or bias within the experiment.

4.3. Procedure

Participants were seated in front of the equipment where they were provided with instructions about the task, as well as a brief explanation of the control scheme. Participants would then complete the experiment task, being stopped after five minutes. Participants would then immediately be asked to complete the SSQ, followed by the Presence Questionnaire. Before repeating the process with the the second condition, participants were offered water and given an opportunity to relax to allow any existing symptoms to subside. After the second exposure, participants would once again complete the SSQ and Presence Questionnaires and then were asked to participate in a semi-structured interview. Once the interview was concluded, and it was assured that a participant had recovered or was recovering, the experiment was concluded. The average time for each condition was approximately fifteen minutes, including calibration, brief and trial time. The entire experiment took between forty minutes and an hour.

Qualitative questionnaires were administered on paper, and were only identifiable by a participant identification number that was given to each participant at the start of the study, allowing for identification of their data should they wish to withdraw. Interviews were recorded and transcribed for thematic analysis.

4.4. Quantitative Measurements

The SSQ [KLBL93] was used to evaluate any negative side effects participants experienced during the exposures. Furthermore, the revised edition of the Witmer and Singer Presence Questionnaire [WS98] was administered after each exposure as a means to gauge engagement. Using these two measurements, the study aims to gain quantitative data relating to cybersickness as well as presence. The collected data can then be used to observe the impacts of somatosensory feedback on a user's sense of presence and cybersickness.

4.5. Qualitative Measurements

Semi-structured interviews were included to improve the understanding of the system and to help understand any findings. A semi-
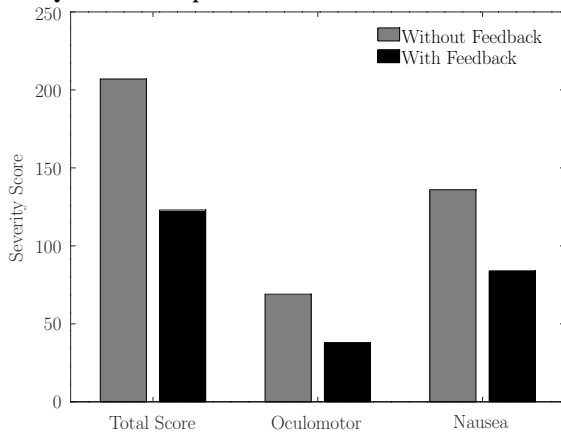
Figure 3: *SSQ sub-scale totals for both somatosensory feedback conditions. Here the sub-scale values relate to the severity of the sickness symptoms. In both symptom categories, subjective sickness was reduced in the condition involving airflow.*
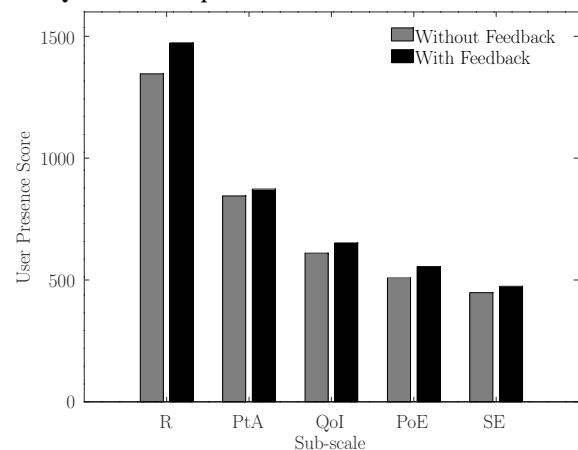

Figure 4: *PQ total scores for each sub-scale (abbreviated). Plotted values are proportional to subjective ratings of user presence, concerning a given sub-scale. It can be seen that higher levels of presence were observed in the condition with somatosensory feedback, across all five sub-scales.*

structured format was chosen over a rigid structure to accommodate the range of uncertainties and human factors present. As such, the questions included are as follows:

- Did you enjoy the experience?
  - Any aspect in particular?
  - Was there any preference for either condition?
- Do you feel VR is a good platform for this type of experience?
- Did you feel comfortable when playing the game?
  - Was there any difference in comfort between sessions?
  - How could this be improved?
- Did you have any other issues when playing the game during either session?
- Would you make any changes to improve immersion or reduce discomfort?
- Any other comments or feedback about either session?
- Are you feeling better since completing the experience?

5. Results

5.1. Scoring the SSQ

The SSQ consists of 16 items listing virtual reality side effects rated from '0' (none) to '3' (severe). A revised and validated version of the questionnaire was used in this study, that reduces the number of examined sub-scales from three to two.

The total mean SSQ for condition A (without airflow) is 5.45 (s.d. = 7.008, range between 0 and 36), and 3.24 (s.d. = 3.405, range between 0 and 15) for condition B (with airflow support). The difference in post-exposure responses to the SSQ for both the experimental and control conditions were analysed using the non-parametric Wilcoxon Signed-Rank Test due to the the ordinal nature of SSQ data and the related participant sample. Participants reported that the condition with airflow feedback (mean =

3.24, median = 2.50) caused less simulator sickness than the control condition (mean = 5.45, median = 3.00). A Wilcoxon Signed-Rank Test indicates that this difference is statistically significant, $T = 357.50, z = -3.058, p = .002, p < .05$. The averages and significance tests for each scoring sub-scale as well as each individual cybersickness symptom can be found in Table 1 with the Ocular-motor and Nausea scales visualised in Figure 3.

5.2. Scoring Presence

The Presence Questionnaire (PQ) consists of 19 items which can each be correlated to different sub-scales of presence. Each item uses a 7 point Likert scale to determine a user's reported sense of presence with regard to a question.

The total mean presence score for the control condition is 99.47 (s.d. = 13.01, range between 69 and 123), and 106.34 (s.d. = 11.49, range between 84 and 127) for the feedback supported condition. Once again, the difference between participant responses for presence questionnaire were analysed using the Wilcoxon Signed-Rank Test due to the ordinal nature of the data and the related participant sample. This test indicates that the results are statistically significant $T = 658.50, z = -4.637, p = .000004, p < .05$. The averages and significance tests for each presence scoring sub-scale can be seen below, and found in Table 2 and the sub-scales are visualised in Figure 4.

5.3. Correlation

To address existing research disputes regarding the nature of the relationship between cybersickness and presence [WS98; Sla99; NHW00], Spearman's ρ correlation coefficient was used with the data from this study to contribute to the discussion. Due to the the uncertainty of the correlation and distribution between the

Symptom / Category	Mean Without Feedback	Mean With Feedback	Statistical Testing
General Discomfort	.74	.45	T = 91.00, z = -2.668, p = .008, p <.05
Fatigue	.18	.13	T = 7.50, z = -1.000, p = .317
Headache	.18	.11	T = 6.00, z = -1.732, p = .083
Eye Strain	.47	.29	T = 108.00, z = -1.698, p = .090
Difficulty Focusing	.32	.24	T = 30.00, z = -1.000, p = .317
Salivation	.37	.39	T = 10.50, z = -.632, p = .527
Sweating	.71	.37	T = 62.00, z = -2.667, p = .08, p <.05
Nausea	.53	.26	T = 33.00, z = -2.157, p = .031, p <.05
Difficulty Concentrating	.18	.03	T = 6.00, z = -1.604, p = .109
Fullness of the Head	.32	.13	T = 24.50, z = -1.897, p = .058
Blurred Vision	.18	.08	T = 12.50, z = -1.414, p = .157
Dizziness With Eyes Open	.32	.13	T = 45.00, z = -1.941, p = .052
Dizziness With Eyes Closed	.29	.18	T = 15.00, z = -.957, p = .339
Vertigo	.13	.11	T = 9.00, z = -.447, p = .655
Stomach Awareness	.45	.32	T = 40.00, z = -1.387, p = .166
Burping	.08	.03	T = 4.50, z = -.816, p = .414
Total Nausea	3.61	2.24	T = 255.00, z = -2.523, p = .012, p <.05
Total Oculomotor	1.84	1.00	T = 170.00, z = -2.461, p = .014, p <.05
Total SSQ	5.45	3.34	T = 357.50, z = -3.058, p = .002, p <.05

Table 1: *Recorded mean and statistical test for each symptom of the SSQ, along with the nausea and oculomotor sub-scales and their totals.*

Category	Mean Without Feedback	Mean With Feedback	Statistical Testing
Realism	35.53	38.89	T = 570.50, z = -4,199, p = .000027, p <.05
Possibility To Act	22.37	23.02	T = 284.50, z = -1.877, p = .061
Quality of Interface	16.21	17.21	T = 326.50, z = -3.353, p = .001, p <.05
Possibility To Examine	13.45	14.68	T = 374.00, z = -3.430, p = .001, p <.05
Self Evaluation	11.92	12.53	T = 225.00, z = 2.180, p = .029, p <.05

Table 2: *Recorded mean and statistical test for each sub-scale of the presence questionnaire.*

two measurements, a two-tailed significance test was used. Results show no significant correlation between the two, $r_s = -.191, p = 0.99, N = 76$. The shallow negative correlation observed aligns closer to Witmer and Singer's results then those of Slater. However, based on the context of the study, the theory that any relationship between the two is governed by a third variable appears most likely [NHW00].

5.4. Thematic Analysis

In order to appraise the verbal feedback of interviews, once transcribed, a thematic analysis was undertaken, following a deductive approach as laid out by Braun and Clarke [BC06]. Codes were constructed with respect to sickness, presence and the context of the study. These codes were then gathered into families which were enriched using particularly defining codes, and the emotional valence of these families were assessed. The themes identified are detailed in the following sections:

Realism - A strong theme identified from the participant base was the value of realism or immersion with respect to a positive experience. Reports elude to a positive correlation between realism and the rate and quality of immersion, as well as a positive correlation between the airflow condition and the fidelity of the virtual experience: "*VR for me is always quite difficult to immerse myself in ... with the fan it actually helped because it kind of set the scene more*", "*Without the airflow you had that separation between game, and not game. Whilst with the airflow it (the separation) is a little more vague*".

Another aspect of realism encountered was the idea of sensory satisfaction where by users expressed that the airflow condition provided a more complete and hence realistic sensory experience: "*I think driving games naturally lend themselves very well to kind of being immersive in the environment, especially when you have a physical steering wheel and physical pedals in addition to kind of wind coming through – like you're hitting a lot of different senses there at once*".

Motion - The focus of the study as a whole surrounds the effects of virtual locomotion and its outcomes. This theme looks at participant's comments regarding their movement through the environment itself rather than the resulting effects. A fairly common observation voiced by the participant base was the lack of inertia during motion, being described as unnatural, with many suggesting a form of self-motion to be incorporated into the system, for example, a hydraulic chair with multiple axes of rotation: "*I feel like if when you go over the sand dunes or anything, if you were actually moving with the vehicle if it felt like you were tilted it would reduce any of the sickness because your body is doing what your brain is telling you that you're doing*", "*The next best thing would be to use, you know, those moving chairs that work and tilt depending on how you move in the game*".

Comfort - Given the nature of the topic, it is unsurprising that a number of interviewees make constructive points regarding the level of comfort, or lack thereof, that they experienced. Participants commented on the difference in condensation forming on the headset lenses that obscured vision: "*The airflow really helped to prevent steaming up my glasses compared to the first time round*". Another benefit of the airflow that was reported is less documentable via questionnaire.

Several users reported being less hesitant to look around during the airflow, either because they were continuously aware of their forward vector, or because of discomfort they experienced during lateral viewing: "*Without the airflow – I found myself having to look forward, like I had to constantly keep focusing on keeping my head looking forward which is basically the same as if I was looking at a screen anyway. So, I couldn't benefit from the use of a headset when the airflow wasn't on because every time I looked sideways I instantly felt sick*". While rare, some negative effects of the feedback system were also reported, which were not anticipated: "*In the session with the fan my salivation increased – I think its because the fan in face was making my throat naturally drier*". Some additional comfort and sickness factors that appeared infrequently in interviews included recovery time being lower after the airflow condition and enjoyment being independent of sickness.

Environment - A number of comments were directed at the virtual and physical environments, and looking at what connects them – the feedback: '*If I was playing a driving game I think I would want it to have much smoother or flat roads*", "*The more rocks and stuff I hit where I felt like I should have been moving and I wasn't that just made me feel a bit queasy and uncomfortable*".

Some interesting, more positive effects of experiencing the digital environment is the psychological interaction with the feedback system. Multiple users reported the sensation of the multi-directional airflow based on whether they are turning within the environment, which was not true in this study: "*I was surprised how well, like when you're turning and stuff how well it actually felt like the wind was on the left of right. It took me by surprise*", "*It was almost a pseudo effect, I knew when I was the fan wasn't hitting me on the side but it felt like it was*". However, this was not unanimous, with many users suggesting directional feedback as a possible enhancement.

Engagement - Engagement was generally positive among participants, however several recurring elements made it an interesting theme. In most cases, airflow was considered an enhancement to the experience, however a number of participants attributed airflow as a means of information feedback due to its dependency with virtual speed: "*With the fan it felt like I was going round faster because the fan was like - going a lot more high-powered*", "*It was just an extra added thing to allow you to perceive the events you being shown basically*". Alternatively some participants saw the airflow as a distraction, but describe it as a distraction from the negative effects rather than hindrance of engagement. "*It might not even reduce the amount of nausea but the constant physical aspect maybe distracted from the nausea*", "*Without airflow it felt as if I was focusing more on the game itself*".

There were also some comments regarding airflow as an general experience enhancement: "*INTERVIEWER: ...did you have any preference between conditions? PARTICIPANT: Definite preference for with airflow ... It felt more visceral and more real, which I suppose is the whole point of VR*", "*I couldn't enjoy it without the airflow*".

6. Discussion

The goal of this experiment was to explore the effects of somatic feedback on users of VR systems. With significant results found via the Simulator Sickness and Presence questionnaires, the relationship between sensory feedback and the measured areas can be argued. This insight is further explained via interviews and thematic analysis.

The quantitative findings regarding sickness for the study proved to be significant when looking at the total reported score, as well as for some sub-scales of the SSQ. By assessing the effects of feedback on the symptoms that comprise cybersickness the efficacy of the system as a preventative can be appraised. General comfort was the most significantly changed symptom, however due to its ambiguous classification its hard to draw conclusions from it alone. Besides general discomfort, sweating was the symptom most affected between conditions. The airflow has a cooling effect on users and consequently reduces the body's need to sweat due to the heat of the headset, as seen in previous work [DBK17]. While it may not hold a significant effect on sweating as a consequence of cybersickness, it reduces the rate at which users become aware of it. In addition to comfort, several users encountered condensation forming on the HMD lenses, impairing system usability which was reduced or nullified during the feedback enhanced condition. Nausea was another symptom that saw statistically significant reductions with the addition of somatic feedback.

The only symptom with an increase in reported severity between conditions was salivation. Interviewees attributed this to the airflow drying their mouths, such that they salivated at an increased rate as a counter-reaction. Vertigo and Burping also have high statistical significance scores, however due to their low baseline frequency and severity this is less concerning to the efficacy of the solution.

While not comprehensive of all sickness symptoms, the somatic feedback system proved effective at reducing some components of the discomfort that comes with VR locomotion. As such it can be argued that, as per our hypotheses, somatosensory feedback has

to potential be operationalised as a means to reduce the level of cybersickness in some VR locomotion environments.

Measuring presence also yielded statistically significant results between the study conditions. The reported change in total presence suggests enhancements in presence in the feedback condition, however some of the sub-scales found significant are unexpected, and should be examined with scepticism. Firstly, of the sub-scales expected to show significance, Realism held the lowest significance value as well as the most polarizing z score. As participants reported during interviews, this was expected for several reasons. These include the increased sensory combination due to another sense being immersed, an increased sense of self-motion and the dynamic feedback changes based on other environmental factors – all of which contribute to a more believable environment with greater fidelity. Similarly, it was anticipated that there would be increased self-evaluation as a consequence of dynamic feedback based on speed. Participants commented on this, however some added that despite the direction of the airflow being fixed, it assisted in determining the direction they were travelling in the environment. This further led to participants being more comfortable with directing their vision away from the direction they were travelling during the feedback condition. Thanks to this, it is believed that the improved understanding regarding velocity is responsible for the significance seen in the self-evaluation sub-scale.

Among the PQ results, some unexpected findings were obtained. Quality of Interface changed significantly in favour of the feedback condition, despite control schemes remaining identical between conditions, leading us to believe that there is a relationship between sensory feedback and utilizing controls. Possibility to Examine was the second sub-scale that unexpectedly returned statistically significant in favour of the feedback condition. The level of detail and interaction capabilities remained constant between conditions, making this outcome surprising, however it may be attributed to similar reasons justifying the studies findings with regards to self-evaluation. Participants mentioned feeling more inclined to view the surrounding environment during the airflow condition which may partly explain this outcome.

The experiment has been successful in addressing the research questions of the paper by investigating both sickness and presence in VR with the support of a somatosensory feedback system. Of these, both measurements found significant results, which supported by thematically analysed interviews, have allowed for deductions regarding the relationship between somatic feedback and VR locomotion. The somatic feedback condition proved effective at both limiting cybersickness while simultaneously enhancing user presence, as hypothesised based on existing research into each field.

Furthermore, our results support the findings of previous work into airflow as a method of feedback. D'Amour et al. [DBK17], found that airflow reduced cybersickness of participants during a passive video experience. Similarly, we observed the same effects using a virtual reality driving game and head-mounted displays. In particular, the inclusion of airflow significantly reduced the cybersickness of participants. In addition, we observed that user presence increased with airflow, which has been established in previous work [KIS*18; RPK*17].

6.1. Future Work

This experiment was a useful venture into the domain of airflow-based somatosensory feedback. However, there are a number of areas which warrant further exploration. Firstly, the system is mono-directional. Whilst this suited the driving simulation used in the experiment, an omni-directional system would provide more flexibility. Secondly, exploring a broader range of challenge environments (beyond driving simulators) would explore the applicability of the system beyond this specific use case.

In addition, the experiment presented in this paper could have used a larger sample size. For this reason, it may be the case that the effects observed in our analysis are limited to our sample. However, considerable effort has been took to reduce this through statistical analysis. This may be an area of future work, in which the same experiment is conducted with a larger sample size.

References

[AH18] AP CENYDD, LLYR and HEADLEAND, CHRISTOPHER J. "Movement Modalities in Virtual Reality: A Case Study from Ocean Rift Examining the Best Practices in Accessibility, Comfort, and Immersion". *IEEE Consumer Electronics Magazine* 8.1 (2018), 30–35 2.

[BBP09] BONATO, FREDERICK, BUBKA, ANDREA, and PALMISANO, STEPHEN. "Combined pitch and roll and cybersickness in a virtual environment". *Aviation, space, and environmental medicine* 80.11 (2009), 941–945 3.

[BC06] BRAUN, VIRGINIA and CLARKE, VICTORIA. "Using thematic analysis in psychology". *Qualitative research in psychology* 3.2 (2006), 77–101 6.

[BL17] BOCKELMAN, PATRICIA and LINGUM, DEANNA. "Factors of Cybersickness". *International Conference on Human-Computer Interaction*. Springer. 2017, 3–8 2.

[Bos07] BOS, JELTE E. "Why cybersickness". *Proceedings of the The First International Symposium on Visually Induced Motion Sickness, Fatigue, and Photosensitive Epileptic Seizures (VIMS2007)*. 2007, 11–17 2, 3.

[DBK17] D'AMOUR, SARAH, BOS, JELTE E, and KESHAVARZ, BEHRANG. "The efficacy of airflow and seat vibration on reducing visually induced motion sickness". *Experimental brain research* 235.9 (2017), 2811–2820 3, 4, 7, 8.

[DNN14] DAVIS, SIMON, NESBITT, KEITH, and NALIVAIKO, EUGENE. "A systematic review of cybersickness". *Proceedings of the 2014 Conference on Interactive Entertainment*. ACM. 2014, 1–9 2.

[FNIM01] FUKUOKA, YUTAKA, NAGATA, TAKANOBU, ISHIDA, AKIMASA, and MINAMITANI, HARUYUKI. "Characteristics of somatosensory feedback in postural control during standing". *IEEE Transactions on neural systems and rehabilitation engineering* 9.2 (2001), 145–153 1, 3.

[GAC*12] GRACE GAERLAN, MARY, ALPERT, PATRICIA T, CROSS, CHAD, et al. "Postural balance in young adults: the role of visual, vestibular and somatosensory systems". *Journal of the American Academy of Nurse Practitioners* 24.6 (2012), 375–381 3.

[HJW*16] HEADLEAND, CHRISTOPHER J, JACKSON, JAMES, WILLIAMS, BENJAMIN, et al. "How the perceived identity of a npc companion influences player behavior". *Transactions on Computational Science XXVIII*. Springer, 2016, 88–107 1.

[KHL90] KENNEDY, RS, HETTINGER, LJ, and LILIENTHAL, MG. "Simulator sickness". *Motion and space sickness* (1990), 317–341 2, 3.

[KIS*18] KUROSAWA, MASATO, IKEI, YASUSHI, SUZUKI, YUJIN, et al. "Airflow for Body Motion Virtual Reality". *International Conference on Human Interface and the Management of Information*. Springer. 2018, 395–402 3, 4, 8.

[KLBL93] KENNEDY, ROBERT S, LANE, NORMAN E, BERBAUM, KEVIN S, and LILIENTHAL, MICHAEL G. "Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness". *The international journal of aviation psychology* 3.3 (1993), 203–220 4.

[Kol95] KOLASINSKI, EUGENIA M. *Simulator Sickness in Virtual Environments*. Tech. rep. Army research inst for the behavioral and social sciences Alexandria VA, 1995 2.

[KRHC15] KESHAVARZ, BEHRANG, RIECKE, BERNHARD E, HETTINGER, LAWRENCE J, and CAMPOS, JENNIFER L. "Vection and visually induced motion sickness: how are they related?": *Frontiers in psychology* 6 (2015), 472 2.

[LaV00] LAVIOLA JR, JOSEPH J. "A discussion of cybersickness in virtual environments". *ACM SIGCHI Bulletin* 32.1 (2000), 47–56 2.

[LDP*02] LIN, JJ-W, DUH, HENRY BEEN-LIRN, PARKER, DONALD E, et al. "Effects of field of view on presence, enjoyment, memory, and simulator sickness in a virtual environment". *Virtual Reality, 2002. Proceedings. IEEE*. IEEE. 2002, 164–171 3.

[LVJ*04] LÉCUYER, ANATOLE, VIDAL, MANUEL, JOLY, OLIVIER, et al. "Can haptic feedback improve the perception of self-motion in virtual reality?": *Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2004. HAPTICS'04. Proceedings. 12th International Symposium on*. IEEE. 2004, 208–215 1.

[MDS17] MUNAFO, JUSTIN, DIEDRICK, MEG, and STOFFREGEN, THOMAS A. "The virtual reality head-mounted display Oculus Rift induces motion sickness and is sexist in its effects". *Experimental brain research* 235.3 (2017), 889–901 2.

[MK04] MOON, TAEYONG and KIM, GERARD J. "Design and evaluation of a wind display for virtual reality". *Proceedings of the ACM symposium on Virtual reality software and technology*. ACM. 2004, 122–128 3, 4.

[Mon90] MONEY, KENNETHE. "Motion sickness and evolution". *Motion and space sickness (A 93-55929 24-52). Boca Raton, FL, CRC Press, Inc., 1990,* (1990), 1–7 2.

[MS92] MCCAULEY, MICHAEL E and SHARKEY, THOMAS J. "Cybersickness: Perception of self-motion in virtual environments". *Presence: Teleoperators & Virtual Environments* 1.3 (1992), 311–318 2.

[NHW00] NICHOLS, SARAH, HALDANE, CLOVISSA, and WILSON, JOHN R. "Measurement of presence and its consequences in virtual environments". *International Journal of Human-Computer Studies* 52.3 (2000), 471–491 5, 6.

[Ocu16] OCULUS. *Oculus Developer Forums: Virtual Reality Motion Sickness VR Simulator Illness Guide*. [Online; accessed 09-August-2019]. 2016. URL: https://forums.oculus.com/developer/discussion/170/virtual-reality-motion-sickness-vr-simulator-illness-guide 1.

[RB75] REASON, JAMES T and BRAND, JOSEPH JOHN. *Motion sickness*. Academic press, 1975 2.

[Rea78] REASON, JAMES T. "Motion sickness adaptation: a neural mismatch model". *Journal of the Royal Society of Medicine* 71.11 (1978), 819–829 1.

[RPK*17] RIETZLER, MICHAEL, PLAUMANN, KATRIN, KRÄNZLE, TARAS, et al. "VaiR: Simulating 3D Airflows in virtual reality". *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM. 2017, 5669–5677 3, 4, 8.

[RS91] RICCIO, GARY E and STOFFREGEN, THOMAS A. "An ecological theory of motion sickness and postural instability". *Ecological psychology* 3.3 (1991), 195–240 2.

[Sla99] SLATER, MEL. "Measuring presence: A response to the Witmer and Singer presence questionnaire". *Presence: Teleoperators and Virtual Environments* 8.5 (1999), 560–565 5.

[SMK98] STANNEY, KAY M, MOURANT, RONALD R, and KENNEDY, ROBERT S. "Human factors issues in virtual environments: A review of the literature". *Presence* 7.4 (1998), 327–351 2.

[Tre77] TREISMAN, MICHEL. "Motion sickness: an evolutionary hypothesis". *Science* 197.4302 (1977), 493–495 2.

[vEdVB11] Van EMMERIK, MARTIJN L, de VRIES, SJOERD C, and BOS, JELTE E. "Internal and external fields of view affect cybersickness". *Displays* 32.4 (2011), 169–174 3.

[Wlo95] WLOKA, MATTHIAS M. "Lag in multiprocessor virtual reality". *Presence: Teleoperators & Virtual Environments* 4.1 (1995), 50–63 2.

[WS98] WITMER, BOB G and SINGER, MICHAEL J. "Measuring presence in virtual environments: A presence questionnaire". *Presence: Teleoperators and virtual environments* 7.3 (1998), 225–240 3–5.

[ZWB*17] ZIELASKO, DANIEL, WEYERS, BENJAMIN, BELLGARDT, MARTIN, et al. "Remain seated: towards fully-immersive desktop VR". *Everyday Virtual Reality (WEVR), 2017 IEEE 3rd Workshop on*. IEEE. 2017, 1–6 2.