HeadBlaster: A Wearable Approach to Simulating Motion Perception using Head-mounted Air Propulsion Jets

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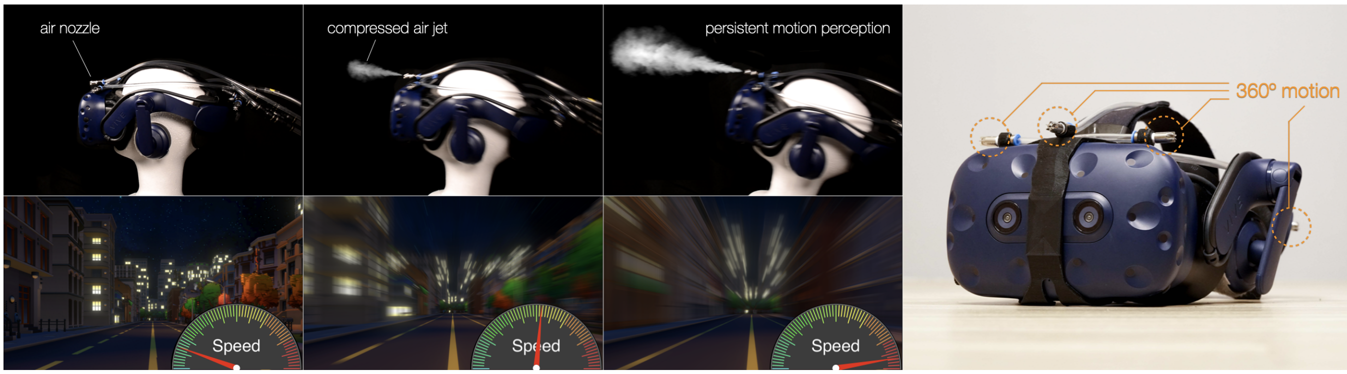

Fig. 1. HeadBlaster: a) applies ungrounded air propulsion force to the head to stimulate the vestibular and proprioception sensory systems to create the perception of persistent self-motion (note: the white smoke is used here only for illustrative purposes; in regular usage, the compressed air is invisible), and b) our system uses 6 air nozzles mounted on VR headsets and combines multiple compressed air jets to generate lateral forces in 360 degrees.

We present HeadBlaster, a novel wearable technology that creates motion perception by applying ungrounded force to the head to stimulate the vestibular and proprioception sensory systems. Compared to motion platforms that tilts the body, HeadBlaster more closely approximates how lateral inertial and centrifugal forces are felt during real motion to provide more persistent motion perception. In addition, because HeadBlaster only actuates the head rather than the entire body, it eliminates the mechanical motion platforms that users must be constrained to, which improves user mobility and enables room-scale VR experiences. We designed a wearable HeadBlaster system with 6 air nozzles integrated into a VR headset, using compressed air jets to provide persistent, lateral propulsion forces. By controlling multiple air jets, it is able to create the perception of lateral acceleration in 360 degrees. We conducted a series of perception and human-factor studies to quantify the head movement, the persistence of perceived acceleration, and the minimal level of detectable forces. We then explored the user experience of HeadBlaster through two VR applications: a custom surfing game, and a commercial driving simulator together with a commercial motion platform. Study results showed that HeadBlaster provided significantly longer perceived duration of acceleration than motion platforms. It also significantly improved realism and immersion, and was preferred by users compared to using VR alone. In addition, it can be used in conjunction with motion platforms to further augment the user experience.

CCS Concepts: • **Human-centered computing → Haptic devices**; *Virtual reality*; *User studies.*

Additional Key Words and Phrases: Motion perception, vestibular system, proprioception

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1 INTRODUCTION

Motion platforms, or motion simulators, create the feelings of being in a real motion environment. They were first invented in 1906, when flight simulators were needed for pilot training as powered aircraft were developed at the beginning of the 20th century [Hancock et al. 2008]. Today, motion platforms are combined with rich visual and sounds to create the sensation of illusory self-motion, called vection, and are popular in arcades, theme parks, and 4D movie theaters. With the recent rise in popularity of VR headsets, interests in consumer motion platforms have been growing rapidly.

Human interpret head and body motion by integrating inputs from our vestibular (semicircular canals and otolith organs), somatosensory (specifically proprioception), and visual systems [Mack et al. 2013]. Visual cues such as displacement and optical flow can create illusion of self-motion called visual vection [Harris et al. 2002; Riecke et al. 2005]. In VR, visual vection that lack vestibular and somatosensory input can cause sensory conflict and lead to visually induced motion sickness (VIMS) [Keshavarz et al. 2015].

Motion platforms physically move and tilt the entire human body to stimulate the vestibular and somatosensory systems, and can provide realistic motion simulation when synchronized with visual vection. However, due to the physical operating range of motion platforms, they can only provide short bursts of actual movement and must stop at their maximum operating range. Thus, the duration of motion sensation is limited as our multi-sensory perception system would soon sense that we are sitting on a tilted surface once the tilting movement stops, partly due to the lack of perceived inertial and centrifugal forces as experienced in real motion.

We present HeadBlaster, a new approach to creating motion perception by applying ungrounded force to the head using air propulsion jets. Compared to motion platforms, which actuate the entire body, HeadBlaster only actuates the head. By applying a lateral force to the head, it causes the head to tilt slightly which stimulates the vestibular system. In addition, because the muscles in the neck and the rest of the body instinctively activate to stabilize the head against the lateral forces and maintain posture, the somatosensory (specifically proprioception) system is stimulated as well. By partially replicating how inertia and centrifugal forces act on the perception systems during real acceleration, the brain interprets these and visual cues as being in real motion. By providing persistent forces, HeadBlaster can create the sensation of persistent acceleration and motion.

In addition, because only small forces need to be applied to the head instead of tilting the entire body, HeadBlaster makes it possible to create wearable designs that do not constrain users to large, mechanical motion platforms. This improves mobility and supports room-scale VR experiences in which users can physically move about to explore the VR environment.

We developed a wearable HeadBlaster system, shown in Figure 1, that uses compressed air jets to provide ungrounded force. It consists of 6 air nozzles pointing in 4 directions: front, back, left (x2), and right (x2). By using multiple programmable compressed air jets, it is capable of creating lateral thrust forces in 360 degrees. In order to reduce noise and improve air usage efficiency, we used industrial air nozzles instead of open pipes, and our system can generate up to 3.8N at 0.7MPa of air pressure. Also, active noise-cancelling headphones are used to further reduce the perceived noise such that it does not affect the user experience.

To understand how head posture is affected by forces applied to the head, we conducted a study that measured the head tilt using an Inertial Measurement Unit (IMU). Results showed 8.2 degrees of average tilt when a 2N force is applied to the head, and that the tilt angle gradually increased during the presence of the force. This indicated that the vestibular system was stimulated as the head tilted, and that the proprioception system was persistently stimulated as muscles in the neck and the rest of the body stabilized the head.

To understand how users perceive the persistence of acceleration, we conducted a perception study and compared HeadBlaster to a commercial motion platform. We created a VR driving experience that simulated 1 minute of lateral acceleration, and asked participants to report the perceived duration of acceleration. Results showed that participants reported significantly longer duration for HeadBlaster than the motion platform by an average factor of 3.4X ($p<.01$).

To evaluate the user experience of HeadBlaster, we created a VR surfing game. Players lean left and right to move sideways, and crouch down to avoid hitting obstacles. Results from our 18-person study showed that HeadBlaster significantly improved the realism of acceleration, immersion, and enjoyment (all $p<.01$), and was preferred by 94% of the participants. To explore the user experience of using HeadBlaster in conjunction with a motion platform, we conducted a study using a commercial VR driving game with a commercial motion platform. Results showed no statistically significant difference between using only HeadBlaster vs. motion platform. However, using HeadBlaster together with the motion platform showed statistically significant improvement in realism of acceleration and immersion ($p<.05$) and was most preferred by 75% of the participants.

In summary, this paper makes the following contributions:

- it presents a new motion perception created by applying ungrounded forces only to the head, to approximate how inertial and centrifugal forces are felt during real acceleration.
- the approach is capable of creating the sensation of persistent acceleration and motion, with significantly longer duration than motion platforms.
- it is the first practical wearable motion simulator that can create realistic motion perception.
- it significantly improves realism and immersion and is preferred by users both when used alone and when used in conjunction with a motion platform.

2 RELATED WORK

2.1 Motion Platforms

Motion platforms were invented for pilot training as powered aircraft were developed at the very beginning of the 20th century – with the first successful powered aircraft being the 1903 Wright Flyer. The first motion platform was the Antoinette's barrel (1906) which was human actuated [Hancock et al. 2008]. The actuation methods evolved from manual, to wind actuation used by Sanders Teacher (1910) on a universal joint [Rolfe and Staples 1988], to pneumatic bellows controlled by the pilot used by the Link Trainer (1929), which supported 3 degrees freedom (3-DoF): pitch, roll, yaw [Baarspul 1990]. The Stewart platform (1965) became a popular design that supports 6 degrees of freedom (6-DoF): 3 rotational pitch, roll, yawand 3 translational/linear (surge, heave, sway), using linear actuators [Stewart 1965].

Today, motion platforms are popular in theme parks, arcades, and 4D movie theaters, and are also used for professional training such as airline pilots and space programs [Beard et al. 2008; Schelter and Masi 1998]. With the recent growing popularity of VR headsets, 2-DoF designs (pitch, roll) and 3-DoF designs (+yaw) that have lower complexity and cost, are becoming readily available for the consumer market to enhance video games, driving/flight simulation, and VR experiences.

2.2 Motion Simulation

In additional to traditional motion platforms, researchers have explored novel approaches to creating motion perception.

Galvanic vestibular stimulation (GVS) uses electricity to stimulate the vestibular afferent nerves from the skin surface [Aoyama et al. 2015; Gálvez-García et al. 2015; Maeda et al. 2005; vMocion 2016; Weech and Troje 2017]. However, GVS has significant side effects and studies have shown that most users experienced mild to moderate pain (91%) and general discomfort (55%), with some reported headache (36%) [Lenggenhager et al. 2008]. While it is capable of generating head sway and rotation for some users, the effects are imprecise and vary significantly across users. In addition, the stimulation fidelity is limited to the vestibular system but not the somatosensory system. As a result, GVS has primarily been demonstrated to reduce VR sickness by reducing sensory mismatch, rather than creating realistic and precise motion simulation.

HapSeat integrated 3 force actuators, specifically the Falcon haptic device, to the headrest and both armrests of a seat to provide haptic feedback to hands and head to create motion sensation without requiring a fully actuated seat [Danieau et al. 2012]. To simulate a car moving forward, it pushes a headrest forward (ie. the car is pulling the user forward), which is the reverse of the inertial force sensation felt by users in a car (ie. head tilting backwards). As a result, while some users reported realistic motion perception, some users reported that the perceived direction of forward acceleration was reversed – as they were expecting to be "pushed backward" into the headrest. In addition, due to the use of a single headrest, HapSeat cannot simulate motion in 360 degrees, and its grounded approach limits user mobility. In contrast, HeadBlaster's egocentric approach addresses possible mismatch in perceived direction of acceleration, and its 360-degree wearable design supports user mobility with motion simulation in 360 degrees.

Haptic Turk leveraged human as mobile actuators to tilt and lift users and to perform actuations that are difficult to engineer [Cheng et al. 2014]. HangerOVER explores an interesting phenomenon, called hanger reflex, in which the head involuntarily rotates when certain pressure is applied to the head [Kon et al. 2018]. The sensation is distinct from motion sensation because it provides tactile stimulation without vestibular/proprioception stimulation. GyroVR integrated flywheels into a VR headset to generate gyroscopic effect that affects the motion of the users to the perpendicular axis of the motion [Gugenheimer et al. 2016]. Although it is also an ungrounded approach as HeadBlaster, GyroVR's effect is perceived as resistance and the effect is only felt when users try to rotate their head against the rotational axis of the spinning flywheel.

2.3 Air Propulsion-based Haptics

Researchers have used air propulsion to provide ungrounded kinesthetic force feedback, which is capable of providing directed force feedback compared to the vibrotactile haptic feedback commonly provided by handheld controllers.

A few projects have explored using compressed air jets to generate ungrounded force. Gurocak et al. used wrist-worn air jets to create size-weight illusion when handling objects in VR [Gurocak et al. 2003]. Jetto integrated a single air nozzle onto a smartwatch to generate lateral force feedback on skin [Gong et al. 2018]. The nozzle rotates 360°and each full rotation takes 2.6 seconds to complete. Because HeadBlaster requires a much faster response time, we used multiple air jets and combined them to create lateral forces in 360° instantly.

Several projects have recently used small, high-speed propellers to create ungrounded force feedback. Thor's Hammer used 6 multi-directional air propellers to create force feedback through a handheld object [Heo et al. 2018]. Leviopole used a similar design to create a handheld haptic pole, both ends of which were equipped with multiple rotors, to generate the illusion of hanging on to a pole and being pulled up [Sasaki et al. 2018]. Aero-plane [Je et al. 2019] used 2 miniature jet propellers mounted to a handheld controller to create the illusion of shifting weights. Wind-blaster, the only wearable design to date, mounted 2 wrist-worn motors and propellers to generate haptic force feedback, and is capable of creating 1.5N of ungrounded force [Je et al. 2018]. The propellers' orientation are rotated using servos.

Although we have used a compressed air design in this paper, a propeller-based HeadBlaster system design would be possible too with different trade-offs. An example wearable propeller design could utilize 16 of Wind-blaster's single-propeller modules mounted on the head in order to generate 3.0N of forces in all 4 directions. Although the head-worn device would be significantly bulkier and heavier, it may be possible to use portable battery packs to eliminate the need of an air compressor. Detailed analysis and comparison of noise, vibration, power curve, and power consumption is beyond the scope of this paper, and will be explored as future work.

3 SYSTEM DESIGN AND EVALUATION

We describe our compressed air system design and evaluate its force, noise, latency, and vibration characteristics.

3.1 Air Nozzles and VR Headset Integration

Our design goal for the wearable part of HeadBlaster is to integrate it with existing VR headsets so that users do not have to put on separate pieces of hardware. We chose Vive Pro for its rigid structure in both the front and the back, and we designed two mounts that clip onto the headset which were 3D-printed using tough PLA material for toughness and durability.

Each mount consists of 3 orthogonal nozzle holders pointing outwards. The holders are C-shaped to simplify the installation of nozzles. As shown in Figure 2 and 3, there are two centered nozzles each pointing towards the front and the back, with two pairs of side nozzles pointing left and right. The center nozzles each has its own inlet pipe. Each pair of nozzles on the same side share the same inlet pipe using a splitter, so that they would simultaneously actuate at the same air pressure to create a net lateral force without rotational torque. We chose this dual side-nozzle design to allow users to freely adjust the length and tension of the headband, and to support the use of headphones.

To reduce noise and improve air usage efficiency, we used industrial air nozzles specifically design for these purposes. The first version (v1) of our prototype used Silvent 209 nozzles shown in Figure 3, which is rated to save 37% of air energy and weighs 65 grams each with push-in fittings. It also reduces noise by 65% compared to open pipe, to a noise level of 80 dB(A) at 1 meter.

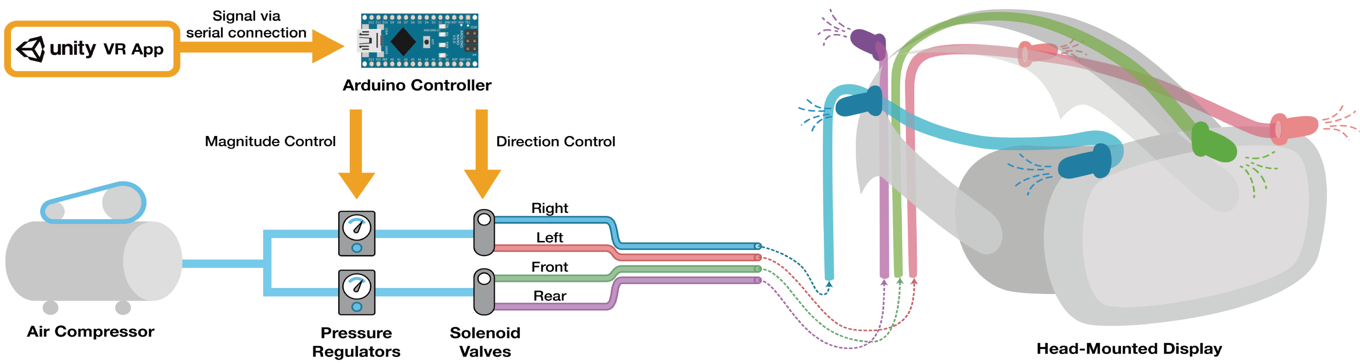

Fig. 2. System architecture diagram showing the 2 pressure regulators that control the magnitude of force, the 4 solenoid valves that control the force direction, and the corresponding 6 air nozzles mounted on a VR headset.

To further reduce noise for the user, we used a Bose QC25 active noise canceling headphones instead of the Vive Pro's built-in headphones, which has an Insertion Loss (IL) of 15-40 dB depending on the frequency band. According to Centers for Disease Control and Prevention (CDC), USA, 80-85dB is equivalent to "City traffic (inside the car)", 70dB is "Washing machine, dishwasher", and 60dB is "Normal conversation, air conditioner". We discuss its effectiveness in noise mitigation in more details in the Discussion section.

3.2 Pneumatic Control System

Our first goal for the pneumatic control system is to be able to create force vectors in any direction at any magnitude by changing air pressure. Instead of using 4 programmable pressure regulators, we simplified the design to use only 2 regulators – by taking advantage of the fact that at most only one of the front/back nozzles and one pair of the left/right nozzles will be active at any given moment.

Our second goal is to be able to reach maximum force magnitude quickly and to update pressure quickly to keep the force vectors in the correct directions as users rotate their heads. We paired two solenoid valves to each pressure regulator for two reasons: 1) to direct air to either one of the front/back or one pair of the left/right nozzles, and 2) because solenoid valve can go from 0% to 100% faster than pressure regulators.

Our current system is driven by an FIAC 4HP soundproof air compressor, which has an operating pressure of 850 kPa and an operating noise of 65dB measured at 1 meter. It has a 50L internal tank and two additional compressed air tanks were used to increase the total capacity to 146L. The tanks are connected via a splitter to 2 SMC ITV2050 electro-pneumatic pressure regulator, which in turn are connected to 2 SMC SYJ712 solenoid valves each. A total of 2 electro-pneumatic regulators and 4 solenoid valves are controlled by an Arduino Nano board that reacts to serial signal input from the same PC that is running the VR experiences and powering the VR headset. We designed a 4-byte structure as input format: the first byte is a header for selecting predefined voltage range profiles, the second and the third bytes represent the normalized pressure output for the two axes, and the least significant four bits of the last byte are used for gate control on solenoid valves. We have open-sourced the Arduino code and Unity API on the PC. [1]

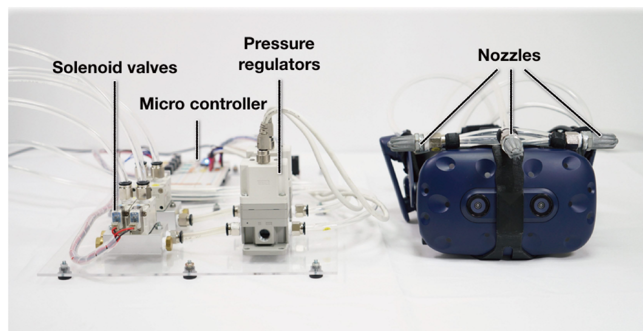

Fig. 3. Photo of the pneumatic components and the Silvent 209 industrial air nozzles (v1) that reduce noise by 65% and improve air usage efficiency by 37%.

3.3 System Evaluation

To understand the force characteristics of our HeadBlaster system, we conducted a series of measurements to characterize our setup.

3.3.1 Stable Air Pressure Range. Due to the underlying mechanics, the programmable regulators require a minimum supply pressure of 100kPa. After empirical testing, we found that lower pressure tended to jitter. We also identified 700 kPa as the lower watermark pressure that our air compressor maintains. The compressor would automatically start once pressure drops below 700 kPa, and would stop after pressure reaches 850 kPa. Therefore, the operating air pressure range for our HeadBlaster system was 100-700kPa.

3.3.2 Air Pressure and Generated Force. We conducted a force measurement study to map the relationship between force and air pressure, using a setup similar to Jetto [Gong et al. 2018] but with a digital force sensor, as shown in Figure 4. The air nozzle was mounted to a ball-bearing platform on a well-lubricated sliding rail, and the platform is connected to the force sensor via a pull cable and the

[1] Open source Arduino and Unity API: https://github.com/ntu-hci-lab/HeadBlaster

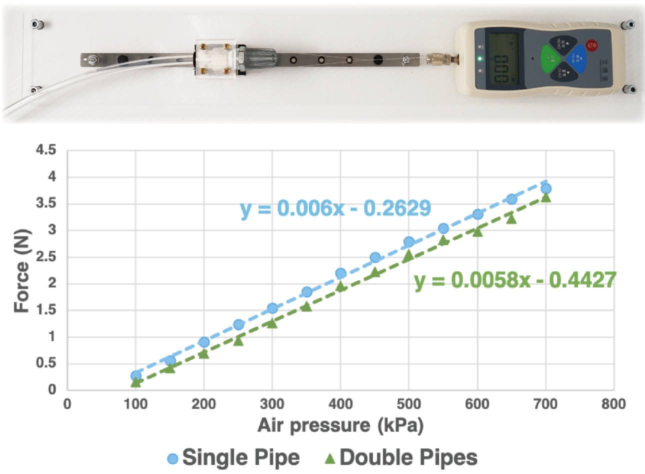

Fig. 4. Top: Apparatus setup for force measurement. Bottom: Relationship between force and air pressure under single-nozzle and two-nozzle settings.

pull force generated by the air jet is measured using the digital force sensor which was rated to 1% precision. . A 3-meter pipe was used to connect the nozzle to the air compressor, which was the same length as the inlet pipes used to connect to the VR headset. We then preformed force measurements under different pressure output from 100 to 700 kPa in 50 kPa steps, for single and dual nozzles. For each pressure step, we measured the force 3 times and averaged the measurements.

Figure 4 shows a force as a linear function of air pressure, and the force generated in the two-nozzle setup was slightly weaker than in a single-nozzle setup as there is additional friction due to the splitter and additional pipe length. Based on the results, we calculated two linear regression models, which we used to calculate the regulator pressure in order to generate a desired force.

3.3.3 Operating Latency. We measured the latency from off to reaching a stable target force between 0.0-3.8N using the single-nozzle force measurement setup, sampling at 240Hz. We found the latency to be 100-150ms when only the solenoid valve is actuated, and 250-350ms when both the pressure regulator and the solenoid valve were actuated, which were all below the 400-500ms latency threshold from previous human factors research for motion systems [Frank et al. 1988; Rank et al. 2010].

3.3.4 Vibration. To understand whether our system produces perceivable vibration, we conducted both a measurement experiment and a 10-person user perception study. As a baseline, we attached a small coin-style vibration motor (12mm, 3.3V, 150Hz) to a Vive Pro headset next to the front air nozzle, and measured vibration using an IMU (450Hz) attached to the headset. The average peak acceleration for the vibration motor was 108x larger than the vibration in the air jet condition. In terms of user perception, we counter-balanced and conducted 2 trials per condition per participant, and asked participants to report whether they felt any vibration. Vibration was reported in 65% of the trials for the vibration motor, and 0% for the air jet.

4 MOTION PERCEPTION

This section provides the neural science background on motion perception and motion simulation [Harris et al. 2002; Mack et al. 2013].

Human's vestibular system, specifically the two otolith organs, the utricle and saccule, detect linear motion as well as the static orientation of the head relative to gravity, which is itself a linear acceleration. In some instances the vestibular input from a receptor may be ambiguous. For example, acceleration signals from the otolith organs do not distinguish between linear acceleration due to true translation and acceleration vs. the tilting of the head (i.e. acceleration due to gravity).

The vestibular system also has different detection thresholds for translation and rotation in different axes. For example, rotation left/right (ie. roll) has lower detection threshold than rotation forward/backward (ie. pitch), and horizontal translation along the Y-axis has lower thresholds than vertical translation in the z-axis [Dupuits et al. 2019; Rey et al. 2016].

In the case of lateral acceleration, both motion platforms and HeadBlaster stimulate the vestibular system by tilting the head. Motion platforms provide short bursts of tilting motion to the entire body before stopping at its maximum tilting angle. HeadBlaster creates head tilt by directly applying ungrounded forces to the head. The vestibular input is ambiguous in both cases. The brain, however, integrates inputs from the semicircular canals, otolith organs, and visual and somatosensory systems to properly interpret head and body motions.

In the case of motion platforms that has stopped at its maximum tilting angle, the somatosensory system senses the lack of lateral forces that corresponds to the inertial and centrifugal forces that would be felt in true acceleration, and determines that the body is sitting or standing on a tilted surface. HeadBlaster, in contrast, provides persistent lateral forces that is consistent with inertial and centrifugal forces, except that it is limited to only the head. Nevertheless, the overall multi-sensory effect is sufficient to create the perception of more persistent motion as interpreted by the brain, as empirically validated in our motion perception duration study.

The rest of this section describe the two human factors studies we conducted to empirically validate the theoretical background. The first study measures the head tilt as ungrounded forces are applied to the head. The second study evaluates the holistic, multi-sensory perception experience of HeadBlaster vs. motion platforms and the perceived duration of motion.

4.1 Vestibular and Somatosensory Stimulation

To understand whether and how head tilts in response to ungrounded forces, we conducted a measurement study with forces applied to the head in 4 directions and in two postures: standing and sitting. Observed head tilt would indicate that the vestibular system is stimulated and that the somatosensory (specifically proprioception) system is stimulated as well because the muscles in the neck and the rest of the body activate to stabilize the head against the lateral forces to maintain posture.

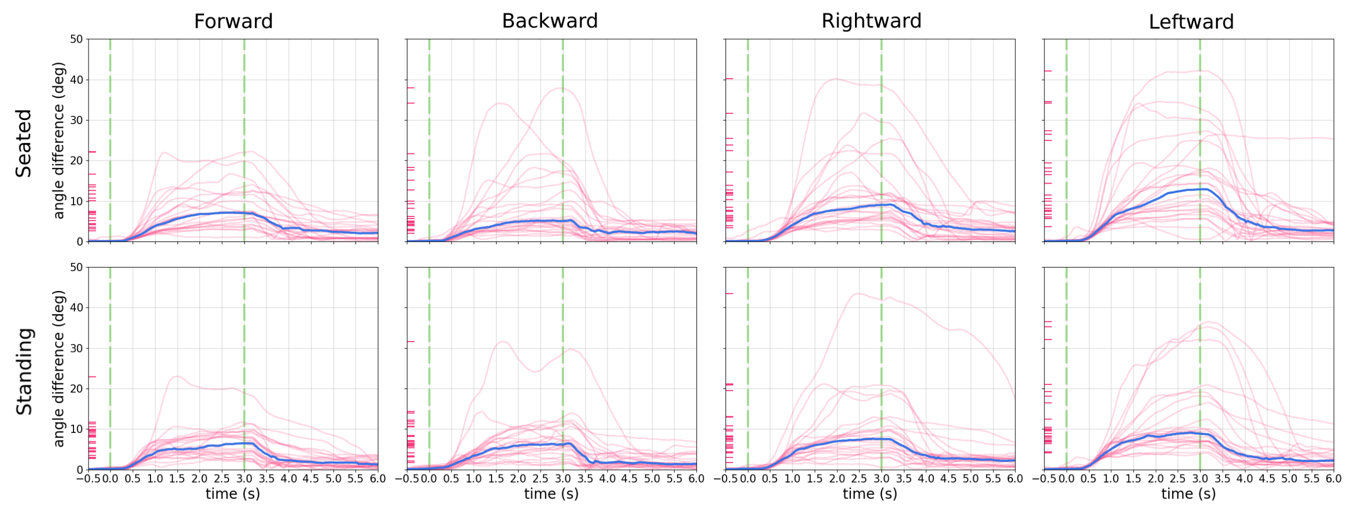

Fig. 5. Head tilt over time as ungrounded forces are applied to the head in 4 directions and in standing/seated postures: the two vertical dashed green lines indicate the start and the end of the forces. Each thin red curve represents a single trial, and the thicker blue curve indicate the median value at each recorded data frame. Each red mark along the Y-axis indicates the maximum tilt angle of a single trial.

The study uses a within-subject design and consisted of 2 sessions, one in seated posture and the other in standing posture in counterbalanced ordering. In each session, the participant was asked to watch an action movie trailer centered in a virtual scene. The trailers were shown on a virtual rectangular TV screen sized to minimize any head movement and vection. To help maintain the attention on the video content, each session played a different trailer and a question about the trailer was asked at the end.

For each session, 2 trials for each of the 4 directions, were generated for a total of 8 force actuations. Each actuation was a constant force at 2N (about 50% of max force) and lasted for 3 seconds, and was separated by a random interval ranging from 5s to 19s to prevent anticipation. The ordering of 4 directions were counterbalanced by Latin square, and the ordering of the randomly generated intervals was the same in all sessions.

12 participants, 6 female and 6 male, age 21-25 with mean age 22.3 (SD = 1.11), were recruited for the study. A constant, low volume white noise was played along with audio from the videos on the Bose QC 25 active noise canceling headphones to mask the noise from the air jets.

We measured head tilt using the DFRobot BNO055 10-DoF Inertial Measurement Unit (IMU) that can sense absolute orientation at 120Hz, mounted onto the front of the Vive Pro headset. The reference head orientation vector for each trial was defined by the average orientation vector during the 1 second before the start of the event. Then, for each frame, an angle difference was calculated against this reference vector.

The results from all trials for all conditions are shown in Figure 5. Because of the large variance across participants, we report the median angles instead of average angles. For the seated posture, the median of max tilt across all users was: forward 7.2°, backward 5.4°, right 9.4°, left 12.9°. For the standing posture, the median of max tilt was: forward 6.7°, backward 6.8°, right 7.9°, and left 9.3°. Across all conditions, the average of median of max tilt was 8.18°(SD = 2.18)

The charts show persistent head tilt in all 8 conditions, with larger tilt in the left/right directions than forward/backward. The tilt angle varied during the presence of ungrounded forces applied to the head, before returning to upright orientation. These suggest that both the vestibular system and the somatosensory system were persistently stimulated while forces were applied.

4.2 Duration of Motion Perception

Human's perceptual system is complex and vary across people. While it in theory can distinguish between sitting on a tilted platform vs. true acceleration, we designed a study to empirically evaluate the multi-sensory perception experience between HeadBlaster and motion platforms. We conducted a within-subject study to compare HeadBlaster to a commercial motion platform, the DOF Reality Consumer H2 model [DOF Reality Motion Simulators 2019], on the perceived duration of motion.

The study was conducted in seated posture for safety, and active noise-canceling headphones were used to mask noises from the air jets and from the motion platform. Participants were placed in a car in VR driving on a circular track, clockwise or counterclockwise. After the participant was cued, a condition-dependent haptic feedback was actuated in the direction corresponding to the visual stimuli. During the trial, participants were given a keyboard for input. They were asked to press any key on the keyboard when they stopped feeling being in motion. We then measured the duration from the start of the haptic actuation to the time where the participant pressed a button. Trials that lasted longer than 60 seconds were terminated and the duration of the trial was counted as 60 seconds. 3 out of 144 trials exceeded 60 seconds, all of which were in HeadBlaster condition.

The study consisted of 6 sessions, at 3 different HeadBlaster force levels and 3 different motion platform speeds. Each session consisted of 2 trials, one in clockwise direction and the other in counterclockwise. In sessions using HeadBlaster, the 3 pressure (force) levels were chosen such that the forces could be stably maintained for 10, 20 and 30 seconds. In sessions using the motion platform, the platform would rotate to its maximum roll angle of 20 degrees over 0.5, 1 or 2 seconds. 0.5 seconds were the measured minimum time to move the platform from center to either end, and we defined the other two levels by doubling the time. Both devices remained unchanged until the end of the trial, though the force of HeadBlaster would drop if the trial lasted longer than the respective duration of stable pressure output.

We recruited 12 participants, 4 female and 8 male, age 18-25, and mean age 22.5 (*SD*=1.6), for the study. The order of the conditions was counterbalanced using Latin square. A total of $6 \times 2 = 12$ trials were performed for each participant.

Results showed that 92% of the participants reported longer duration of motion perceived for HeadBlaster vs. the motion platform. The average perceived duration for HeadBlaster was 3.4 times as long as the motion platform (mean=18.8 vs. 5.5s, *SD*=16.7 vs. 4.0), and analysis with Wilcoxon signed-rank test showed that the difference was statistically significant (two-tailed p = 0.005).

5 DESIGNING FORCE FEEDBACK FOR HEADBLASTER

We describe how we design the force output to conserve air energy and how to map the force output to acceleration in virtual experiences.

5.1 Absolute Detection Threshold (ADT)

To conserve air usage, the air jets can be turned off completely when the ungrounded force is so weak that it is undetectable by users (ie. below the absolute detection threshold).

To determine the absolute detection threshold, we conducted a psychophysical study that followed a standard two-down one-up staircase sensitivity study design [Jones and Tan 2012; Leek 2001]:

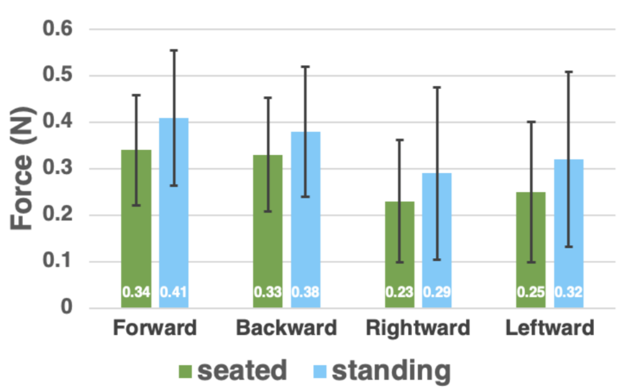

Fig. 6. The average minimum detectable force from the absolute detection threshold study.

- For each trial, the device generates a target force for two seconds. Each trial is followed by a five-second break.
- If the user confirms that the force is felt via verbal response twice in a row, the target force is lowered by a defined step size. Else, the target force is increased by a step size.
- A *reversal* indicates a trial where the user begins to feel the force after an increase or the user cannot feel the force after a decrease.
- Starting from 2N, a force level determined from our pilot testing that can be clearly felt, the initial step size is 0.4N, 20% of the starting force. Upon the first reversal, the step size is halved (0.2N).
- A session is complete upon the fifth reversal. The force levels of the last four reversals are averaged and used as the result threshold.

To examine the effects of directions and postures, we performed two sessions for each combination of the 4 directions and 2 postures (standing vs. sitting), for a total of $2 \times 4 \times 2 = 16$ staircase sessions for each participant.

We recruited 12 participants, 6 female and 6 male, aged 16 to 26, mean age 22.5 (*SD*=2.54), for the study. The order for the directions and postures was counterbalanced by Latin square. Each staircase session was followed by a ten-minute break.

The results showed that the threshold differs between different combinations of directions and postures as illustrated in Figure 6. We performed a two-way repeated measures ANOVA to examine the effect of directions and postures, and the statistical analysis showed that the thresholds under seated posture are significantly lower than those under standing posture (p=.003).

It also showed that the detection thresholds for the left/right directions are significantly lower than those in the forward/backward directions (Forward-Right p=.016, Forward-Left p=.001, Backward-Right p=.004, Backward-Left p=.008). Interestingly, this matches the vestibular perception having lower thresholds for left/right rotation vs. forward/backward rotation [Dupuits et al. 2019]. Last, the two directions along either axis have no significant effect between each other (Forward-Backward p=.532, Left-Right p=.221). This is

5.2 Mapping Virtual Acceleration to Force Output

There are many approaches to design force mapping functions to acceleration, with different tradeoffs. Here we describe an example mapping function that preserves the dynamic range of acceleration to minimize clipping, by linearly mapping the range of acceleration to the range of force output above the absolute detection threshold.

Given a virtual acceleration G_{now}, and a defined set of lower and upper bound of acceleration G_{min} and G_{max}, we can compute the intensity I for the current frame as follows:

$$I = min(1, max(0, \frac{(G_{now} - G_{min})}{(G_{max} - G_{min})}))$$

The computed intensity I can be further transformed into hardware space by computing output force F with the system maximum output bound F_{max} and the minimum detection threshold F_{ADT}:

$$F = \begin{cases} I \times (F_{max} - F_{ADT}) + F_{ADT}, & \text{if } I > 0 \\ 0 & \text{otherwise} \end{cases}$$

This mapping function utilizes the entire force output range above ADT, which avoids clipping and works well when the range of virtual acceleration is large. However, when the range of acceleration is small, some small acceleration may be overly emphasized by mapping G_{max} with a small absolute value to too large of a force output, and vice versa. Other approaches may aim to be more realistic or more entertaining, and we plan to explore the design spectrum of mapping functions as future work.

6 USER EXPERIENCE EVALUATION

We evaluated the user experience of HeadBlaster through two VR applications to understand its effect on realism, immersion, enjoyment, and preference. The first was a custom VR surfing game in which the player use body movement to control the avatar, which would not be safe or possible on a motion platform. The second was a commercial driving game. We compared HeadBlaster to a commercial motion platform, and also how HeadBlaster augments that experience.

6.1 Application: VR Surfing Game

Players lean their bodies left/right as shown in Figure 7 to change the surfing direction of the avatar. Black fog slows the player down, and green power-ups boost speed. To avoid hitting the bridges on the river, players have to dodge them by crouching down. The height of the bridges is calibrated to 90% of the player's height. A summary of the haptic stimuli during the experience is as follows:

- The player automatically and gradually accelerates to a predefined speed limit, generating a backward inertial force that gradually weakens as the player approaches the speed limit.
- When the player enters black clouds, a forward inertial force is generated to correspond to deceleration.
- When the player triggers a speed boost, a backward inertial force is generated to correspond to acceleration.

Because the player can rotate their head freely during the experience, the output force vector is rotated by the inverse rotation of the tracked headset before sending the signal to the controller board in order to apply the force in the correct direction.

6.1.1 User Study. To evaluate the user experience of HeadBlaster we conducted a user study using the surfing game. The study consisted of two levels, with and without HeadBlaster, performed in a two-session within-subject design with the ordering counterbalanced. We had considered other baselines to compare HeadBlaster to. However, vibration does not provide motion simulation, HapSeat is not suitable for 360° VR experiences, and Galvanic Vestibular Stimulation has too serious of comfort issues to be practical. Therefore, we compared HeadBlaster to a baseline of no haptic feedback in this study, and the comparison to motion platforms is done in the next study.

Experimental Procedure. The participant filled out a form for basic information before we briefed them on the control scheme and game mechanics. We demonstrated the controls and the participants

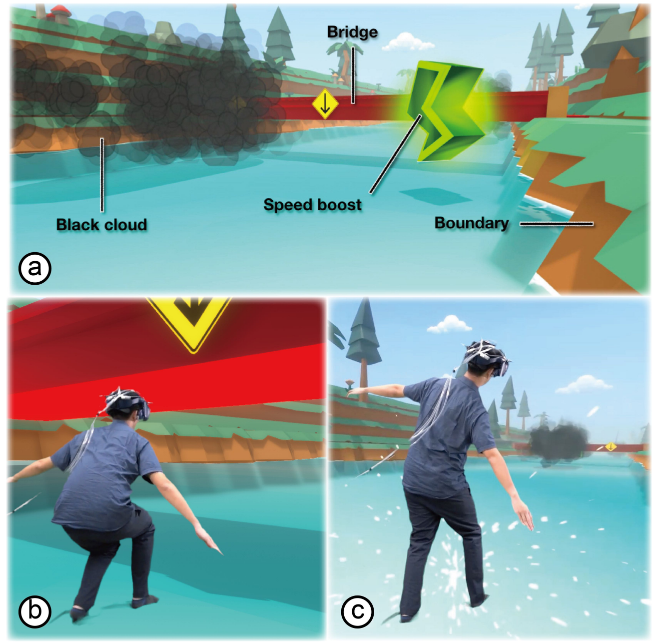

Fig. 7. (a) An overview of the key objects in the surfing game. (b) The player crouches to avoid hitting a bridge. (c) The player leans their body to move left and right.

practiced to ensure they could comfortably control their avatar through body motion. HeadBlaster was worn in both conditions to prevent the weight sensation from affecting the results, and the Bose QC25 active noise-cancelling headphone was worn and played game sounds to mask the noise.

Participants were then asked to rate realism, immersion, and enjoyment using 7-point Likert scales, as well as overall preference and qualitative feedback. Specifically, participants were asked "How much did the acceleration/deceleration seem consistent with your real world experiences?" and "How completely were you immersed in this virtual experience?", adapted from the Presence Questionnaire (version 3)'s question 7 and 23, respectively [Witmer et al. 2005].

Participants. 18 participants, 9 female and 9 male, age 19 to 27, mean age 23.3 (*SD*=2.6), were recruited for the study. All participants had normal or corrected to normal vision and limited exposure to VR: 9 had experienced VR no more often than once a year, 2 no more than once a month and 7 had never.

6.1.2 Results. We performed Wilcoxon signed-rank tests for analysis, and the result, as displayed in 8, showed that playing the game with HeadBlaster was a significantly better experience than without HeadBlaster in terms of realism of acceleration (HeadBlaster: mean=6.00, *SD*=.69; baseline: mean=5.06, *SD*=1.11; one-tailed p=.002), immersion (HeadBlaster: mean=6.33, *SD*=.77, baseline: mean=5.39, *SD*=1.20; one-tailed p=.001) and enjoyment (HeadBlaster: mean=6.61, *SD*=.50, baseline: mean=5.83, *SD*=.92; one-tailed

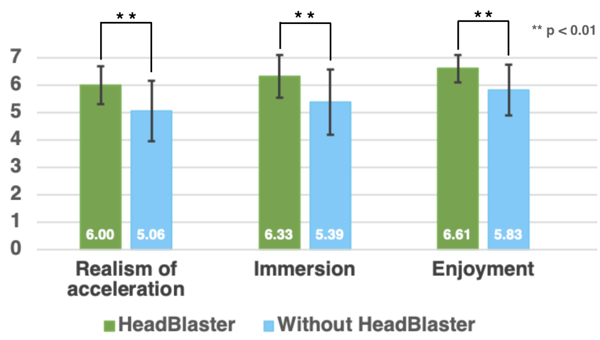

Fig. 8. Average ratings of realism, immersion, and enjoyment on a 7-point Likert scale from the surfing game, with and without HeadBlaster. HeadBlaster significantly improved all these compared to the baseline (p <0.01).

p=.0005). In terms of preference ranking, 94.4% of participants preferred the surfing experience with HeadBlaster.

Qualitative feedback. Participants commented that "the feeling of motion makes this game more real and exciting" (P4) and "It is amazing that when I get a speed boost, there really is a force pushing me forward!" (P10). However, "the force is a bit too strong," (P11) and "the headset feels heavy" (P7).

6.2 Application: Commercial Driving Simulator

As HeadBlaster is capable of providing persistent motion perception, we are interested in whether it augments the user experience when used in conjunction with a motion platform.

6.2.1 Integrating HeadBlaster with commercial driving simulator. Since motion platforms are commonly used to enhance the realism for driving simulation, most realistic car simulators and games provide a telemetry API for external software and hardware to read the in-game vehicle info via UDP port or shared memory. We integrate our HeadBlaster haptic system with these applications. After testing with several games, we chose Assetto Corsa [Kunos Simulazioni 2014a] as the testbed for our study because of its high realism, VR support, and ease of custom modification.

One issue we faced during integration was that the info structure sent from Assetto Corsa includes the acceleration data in the car space but not in the view space, and no view rotation data was sent [Kunos Simulazioni 2014b]. For haptic devices that are fixed on the user's head, it may cause the force to be applied in an incorrect direction when the user turns their head left or right during driving. To work around this, we created an OpenVR background application to monitor the head rotation and computed the correct force direction as we did in the surfing game.

We utilized the longitudinal and lateral acceleration data obtained from the telemetry to compute the haptic force. To render only meaningful haptic feedback, as a preliminary methodology, we recorded the acceleration data when driving across a lap using a specific car model, and we defined the upper and lower bounds of force for rendering haptics based on the dynamic range analysis. These bounds were used in the formula shown in section 5.2 as G_{max} and G_{min} respectively to compute the force output. Because the average velocity varies among different car models, per-model analysis may help optimize the haptic experience. For the study, we chose Ferrari 458 GT2 model and set the bounds to 0.3G - 1G based on analysis and empirical testing.

Fig. 9. HeadBlaster device is used with motion platforms to provide persistent motion sensation to further augment the VR driving experience.

6.2.2 User study. The study consisted of three conditions of hardware setup: HeadBlaster only, motion platform only, and both, performed in a three-session within-subject design.

Apparatus. We installed a racing seat and Logitech G29 Driving Force controller set on the DOF Reality Consumer H2 motion platform to create an authentic car simulation environment. A Bose QC25 active noise-cancelling headphone with in-game sound effects was used to prevent the noise from affecting the perception. The participants were seated on the platform and played the simulator with Vive Pro HMD with HeadBlaster in all conditions.

As the driving technique varies among users, to control the quality of the experience, we used a wide empty custom map with no colliding obstacles for the study. The texture of the ground was changed to grids to enhance the visual perception of speed with static reference. Auto gear shift was enabled in all sessions to help participants focus on the driving experience.

Experimental Procedure. The participant filled out a form for basic information before we explained the VR experience and the study procedure. We demonstrated how to throttle, brake and steer the car and asked the participant to practice performing them. For each condition/session, we verbally delivered two sets of instructions in a fixed order through line-in to the headphone for the participant to follow. Each set, comprising of throttling, braking, and steering left and right for a fixed period varying from three to five seconds, took a total of thirty seconds to complete. A brief break was taken between the two sets. After both sets were complete and another

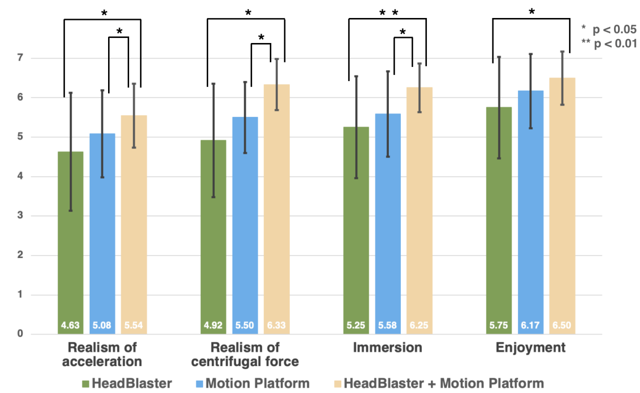

Fig. 10. Average rating of realism, immersion, and enjoyment on a 7-point Likert scale from playing VR driving experience using: 1) HeadBlaster only, 2) motion platform only, and 3) both. No statistically significant differences were found between HeadBlaster and motion platform. However, using HeadBlaster and motion platform together significantly improved realism, immersion, and enjoyment compared to HeadBlaster (p<.05), and significantly improved realism and immersion compared to motion platform (p<.05).

break was taken, we asked the participant to freely drive on the course for 10 seconds.

In the pre-experiment form, we asked for the age, gender, frequency of exposure to VR and motion platforms, and frequency of driving. In the post-session questionnaire, we asked participants to rate the realism of acceleration/deceleration and centrifugal force, immersion, and enjoyment on a 7-point Likert-scale. After all three sessions were completed, participants were asked to provide overall preference and qualitative feedback.

Participants. 12 participants, 5 females and 7 males, aged 18 to 25, mean age 21.8 (SD=2.0), who did not participate in the previous surfing study were recruited for this study. All participants had normal or corrected to normal vision and no participants had experience with VR more often than once per three months. Four participants had experience of driving. All but two participants had experienced motion platforms at theme parks, arcades, and theaters. The ordering for three conditions was counterbalanced.

6.2.3 Results. We performed pairwise Wilcoxon signed-rank test for statistical analysis because not all 3 conditions were fully independent. The results, as shown in Figure 10, showed no statistically significant difference between HeadBlaster and motion platform (one-tailed p>.1 for all). Using both together provided significantly improved experience than using either device alone in terms of realism of acceleration, centrifugal forces, and immersion (one-tailed p<.05 for all). Though enjoyment was rated higher compared to using motion platform alone (mean=6.50 vs. 6.17), it was only significant at the .1 level (one-tailed p=.063). In terms of preference ranking, 75% of participants most preferred using both together, vs. 17% and 8% for motion platform and HeadBlaster, respectively.

Qualitative feedback. Participants commented that "I liked HeadBlaster with motion platform the best. The experience was fun." (P10) "Compared to HeadBlaster, motion platform made stronger sensation when accelerating." (P9) "It felt more exciting when my head was pushed when turning." (P1) "HeadBlaster with motion platform made realistic feeling of centrifugal force." (P5)

7 DISCUSSION AND LIMITATIONS

7.1 Noise Mitigation

The air nozzles that we selected are designed to reduce air noise by 65% compared to open pipes. To further reduce noise, we used a Bose QC25 active noise canceling headphones, which has an Insertion Loss (IL) of 15-40 dB depending on the frequency band. Compared to drone propellers that typically rotate at 30K+ rpm and have high-pitched noise profile often described as swarm of bees, the noise profile of HeadBlaster's industrial air nozzles is similar to white noise, which active noise-canceling headphones are especially effective at reducing.

In practice, the air jet noise can be masked with low to moderate game music and sounds for the HeadBlaster users. Because there was no game music and sounds for the Absolute Detection Threshold study and the Persistence of Motion Perception study, a constant white noise was played. At the end of the session for each participant, we explained how HeadBlaster worked then specifically asked whether any noise was heard during the study. 0 participants reported that they noticed any noise.

In summary, while air propulsion system can be noisy, the use of noise-reducing nozzles, air compressor with sound insulation, active noise-canceling headphones, and game music/sounds can reduce and mask the noise sufficiently such that it is not noticeable by HeadBlaster users. However, the noise is still distracting to people nearby who are not wearing noise-canceling headphones.

7.2 Device Weight and Form Factor

Several users from our studies reported that the HeadBlaster headset was heavy. This was due to the Silvent 209 industrial stainless steel nozzles we used in version 1 of our system. Each nozzle with connector weighed 65 grams, for a total of 435g including 6 nozzles plus two 3D-printed mounts. With 3 meters of 8mm tubing (at 24 g/meter), the total wearable weight would be 507g.

Based on the feedback, we found much smaller and lighter Silvent 1011 nozzles, for version 2 (v2) of our system, shown in Figure 1. It is also rated to reduce noise by 65% compared to open pipes, and is significantly lighter at 8 grams each. With 3 meters of 6mm tubing (at 16 gram/meter), the total wearable weight of HeadBlaster would be 141g for a 72% weight reduction. However, it has a tradeoff of 20% lower maximum force output at 3.0N due to the use of smaller tubing.

The 141g weight of our v2 design is comparable to a single set of Wind-blaster at 167g (which also includes the weight of the Arduino board and 2 servos). Because each set of Wind-blaster provides 1.5N output, 8 sets of propellers would be needed to generate 360-degree force output up to 3.0N (sans the weight for the servos and microcontroller boards). In terms of form factor, the miniature air nozzles are small and easily integrated into the headset design. Each mini nozzles takes up about 3% of the volume compared to each of Windblaster's single propellers (diameter of 12 vs. 67mm and height of 33 vs. 39mm), and 6 nozzles are needed vs. 16 single propellers.

7.3 Degrees of Freedom and Direction of Forces

Our HeadBlaster system currently supports lateral motion perception in 360 degrees, which cover many common motion experiences. The rotational DoF, yaw, could help create torque sensation as well as actively guide users' attention in a virtual environment. This could be supported by our current nozzle design by adding two additional valves to enable the independent control of all nozzles. By actuating the diagonally positioned left/right nozzles, a rotational force could be generated, and we are looking into understanding this new perception. We are also exploring designs to create the perception of heave, which is vertical translation/linear motion along Z-axis.

One limitation of our fixed nozzle design is that the direction of propulsion forces are fixed relative to the head, rather than the horizontal plane. For small head tilt angles, such as the median of 10° observed from our study, there is a reduction of 1.5% in the magnitude of the horizontal component of force vector. Larger head tilt angle of 20° and 30° would lead to a reduction of 7.0% and 13.4% in the horizontal component of the force vector. While the reduction in magnitude may be small, it remains to be explored how the changes in angle affect motion perception, and we are looking into designs that auto-level the nozzles.

7.4 Practicality of Compressed Air Jets

We actually discovered this new motion perception by accident while we were using air propulsion for another project. Throughout the many user studies, one consistent feedback we heard from users was how surprisingly realistic the motion sensation was, even though the forces were only applied to the head but not the body.

While our wearable design eliminates the mechanical platform and has a much smaller footprint, there are some limitations. First, the air jets are quite powerful and can easily blow light objects like empty paper cups off a table. That means a distance of about 1 meter needs to be maintained around users of HeadBlaster. Second, users are still tethered via tubing to air compressors. SCUBA diving tanks operate at 20-30 times higher pressure than typical air compressors, and we are looking into using portable high-pressure air tanks so that HeadBlaster can be truly mobile.

In addition, we have been using off-the-shelf industrial pneumatic components that are designed for manufacturing automation, which have very different design goals than home and commercial VR usage. As we iterated on the engineering of our system, we have noticed several opportunities to improve the practicality and user experience for consumer use. First, air compressors generally have a powerful motor that cycles between being completely on and completely off. It would be less noisy to be able to dynamically scale the level of output, and thus noise. Second, the air nozzles typically stainless, instead of the much lighter aluminum, to provide resistance to heat and chemical. Designing nozzles for HeadBlaster would optimize for noise, weight, and maximizing propulsion forces.

7.5 VR Sickness

VR sickness is a major barrier to using VR, and galvanic vestibular stimulation (GVS), bone-conducted vibration [Weech et al. 2018], and WalkingVibe [Peng et al. 2020] have shown that "noisy" or imprecise vestibular stimulation helps reduce VR sickness. HeadBlaster can more precisely reduce sensory conflict, which has the potential to more effectively reduce VR sickness as well as improve the realism of locomotion. We are currently exploring its effectiveness and whether a much weaker force can be used, to significantly reduce system size and noise.

8 CONCLUSION

This paper presented the first practical wearable motion simulator, with the following contributions: 1) a new motion perception created by applying ungrounded forces to the head, to approximate how inertial and centrifugal forces are felt during real acceleration, 2) the approach is capable of creating the sensation of persistent lateral acceleration and motion, with significantly longer perceived duration compared to motion platforms, 3) it enables wearable designs that improves user mobility, 4) it significantly improves user experience in terms of realism and immersion, and is preferred by users both when used on its own and when used in conjunction with a motion platform.

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