# BreathVR: Leveraging Breathing as a Directly Controlled Interface for Virtual Reality Games

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## ABSTRACT
With virtual reality head-mounted displays rapidly becoming accessible to mass audiences, there is growing interest in new forms of natural input techniques to enhance immersion and engagement for players. Research has explored physiological input for enhancing immersion in single player games through indirectly controlled signals like heart rate or galvanic skin response. In this paper, we propose breathing as a directly controlled physiological signal that can facilitate unique and engaging play experiences through natural interaction in single and multiplayer virtual reality games. Our study ($N = 16$) shows that participants report a higher sense of presence and find the gameplay more fun and challenging when using our breathing actions. From study observations and analysis we present five design strategies that can aid virtual reality game designers interested in using directly controlled forms of physiological input.

## ACM Classification Keywords
H.5.1. Information Interfaces and Presentation (e.g. HCI) : Artificial, augmented, and virtual realities

## Author Keywords
Virtual Reality, Physiological Control, Breathing Actions, Game Design

## INTRODUCTION
Virtual reality (VR) offers enough visual and auditory cues for our perceptual system to interpret the computer generated environment as a ‘place’ even though we are aware of the fact that the ’place’ does not exist. This sense of being in a place is referred to as presence [32]. The vision of VR has been to create worlds that look, sound, act, and feel real [36]. While complete perceptual equivalence between real and virtual worlds is not yet possible, there is a subjective threshold at which interactions in VR feel natural and the virtual world seems real [20]. One way to enhance the sense of realism and presence is to integrate natural interaction techniques in VR.

From text-based multiuser dungeons (MUDs) to rich graphical and sensorial experiences in VR, gaming applications have evolved tremendously. Simultaneous advances in hardware technologies have resulted in a proliferation of low-cost devices that can sense the user’s motion. Realtime motion sensing has enabled more natural interactions with games than has been possible through keyboards or joysticks. Sensing devices range from handheld controllers, that can be used for gesture-based input like the Nintendo Wiimote, to depth cameras that use computer vision techniques to estimate the full body pose for multiple users, such as the Microsoft Kinect. Physiological input for game interaction is another method that can provide natural and realistic gaming experiences and has been explored since the early 1980s [23]. The Nintendo 64 biosensor (1998) measured user’s heart rate and adapted the speed in Tetris 64 accordingly while the Wii Vitality sensor (2009), a pulse oximeter connected to the Wimote, was designed for use in relaxation games.

Common physiological signals used in digital applications are heart rate (HR), galvanic skin response (GSR) or electrodermal activity (EDA), electroencephalogram (EEG), electromyography (EMG), motion, gaze, respiration, and temperature. Physiological signals fall into two main categories, those that are directly controlled, and those that are indirectly controlled. Nacke et al. [23] define direct physiological control as measures that a user can manipulate (e.g., muscle flexion, eye gaze) versus indirect physiological control which refers to measures that change only as an indirect result of other bodily activation (e.g., HR, GSR). Each category affords different types of interactions in gaming applications. HR and GSR signals have been used as replacements for game controllers to teach relaxation skills [23, 25]. Indirect signals have been used in competitive games where the player must try to excite themselves to win the game [3, 13]. Physiological signals in VR have been used for a wider variety of applications in areas of sports training (motion tracking) [11], balance and mobility (force plate) [5], and treatment of generalized anxiety disorder (HR and GSR) [24]. Despite several explorations around physiological signals in both VR and non-VR applications, designing for directly controlled signals as input for games has not been readily explored.

In this paper, we present breathing as a directly controlled physiological input method that works in conjunction with

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handheld controllers to create immersive VR gameplay experiences. We describe the design of four breathing actions and the implementation of two games to investigate our novel breath control input mechanism. The first game is a first-person shooter or FPS game in the style of currently popular wave-shooters in VR. It features enemies that spawn continuously in all directions and make their way to the user in the center. The game attempts to balance the number and frequency of enemies over time to generate flow for both novice and experienced players [7, 10]. In addition to pressing triggers on the controllers to shoot, players have a range of attack "superpowers" actuated by performing breathing actions. The second is a competitive game that involves two players at opposite ends of a corridor facing each other. Each player gets a ball on their turn that they throw towards the opposing player. The goal is to get the ball past the opponent for scoring a point. Both players can deflect the ball with their hand controllers. They can also manipulate the ball with "superpowers" that are activated by the breathing actions.

Our directly controlled physiological input is based on four breathing actions: *gale*, blowing out long and hard like blowing out candles on a birthday cake; *gust*, blowing out a short and fast puff of air like blowing away dust on a surface; *waft*, gently blowing out with an open mouth like breathing on a cold window to write with your finger, and *calm*, taking a deep breath and holding it for a few seconds. The actions are mapped to appropriate actions and effects in each game. Our study ($N = 16$) shows that players enjoy using physiological input; that presence is higher in breathing versus non-breathing gameplay; that users predominantly prefer one breathing action; that breathing actions can be challenging to use in physically intensive games; and that breathing actions can be easily and effectively integrated into the design of VR games.

With this work we aim to encourage designers to consider breathing as a directly controlled physiological input for enhancing immersion in VR games. The contributions of our work are as follows:

- Concept, design and implementation of four breathing actions for interaction in VR.
- Two game implementations that exemplify the natural mapping of breathing actions to effects in the virtual world.
- Findings from the user study on the strengths and shortcomings of using breathing actions.
- Five design strategies for VR game designers who want to utilize physiological sensing in their practice.

## RELATED WORK

The work presented in this paper explores the use of breathing actions as input in single and multiplayer virtual reality games. We summarize below some of the most directly related works in areas of VR games, natural interaction, physiological sensing for enhancing immersion and engagement, and breathing in VR applications.

### Natural Interaction

The most important factor behind presence in VR is perception through natural sensorimotor contingencies, i.e., the more the body is directly involved in the process of interaction, the more natural the virtual experience [31]. Every physical action in the real world involves a gesture of some sort defined as "...a motion of the body that contains information " [4]. Gesture-based interaction has been extensively explored in HCI as a richer form of interacting with digital devices than traditional input methods. One of the first hand-to-machine interface devices, the DataGlove, provided real-time gesture, position and orientation information [41] and was used for several early VR applications [6, 19]. While, hand worn devices can be cumbersome and inaccurate, camera based devices can mitigate that burden and detect mid-air hand gestures with increasing accuracy [37]. To add to VR research on natural input methods, we introduce breathing as a modality to augment the primary input device, which in our setup is the HTC Vive hand controller.

### Physiological Signals

Physiological input for game interaction has been explored since the early '80s [23]. Affective games are a specific genre of physiological games that employ data about "the player's current emotional state ... to manipulate gameplay" [12]. However, replacing conventional input with biological signals does not by itself make a game affective. To become affective, a game needs to propagate affective feedback [3]. For instance, Bersak et al. [3] utilized GSR to control a racing game where participants needed to relax in order to win the competition. On the contrary, GSR and EEG signals were utilized to control a game where players needed to stay excited to win the game [13]. Non-affective games have used facial expressions to replace a game controller through an expression recognition system [22]. Nacke et al. [23] leveraged a set of physiological signals (e.g., respiration, gaze, and EMG) as direct input controls in a computer game.

Breathing has been explored as a control mechanism to influence the physical world and the virtual environment, mostly in indirect ways. Schnadelbach et al. [29, 30] externalize physiological data in the form of a tent-like structure by mapping breathing to its shape and size. Hook et al. [14] devised a room that synchronized the brightness of the bulbs with a user's breathing. Marshall and colleagues [21] built an amusement park game where bumping and rolling intensity was impacted by the rider's breathing rate. Alakarppa et al. [1] proposed using breathing to create an ephemeral interface where users could draw pictures. Direct breath-control mechanisms have been relatively less investigated. In commercial games like Zelda Spirit Tracks (Nintendo DS) or Invizimals (Sony PSP) the microphone is used to detect blowing out. Zielasko et al. [40] use blowing into a microphone to realize a trigger in a CAVE setup. Sonne and Jensen [34] proposed a respiration game for children with ADHD that aimed to "be calming and still sustain their attention." They mapped the amount of exhalation flow to the position of a character on the screen. Tennent et al. [38] developed a wearable respiration mask that was capable of measuring breathing airflow. They designed five small games with the mask, two among which were direct breath-control games, both using the waveform of breathing to manage the game characters. To the best of our knowledge, previous works have only used breathing rate and volume for interaction. In contrast, we leverage breathing as a gesture-based interaction technique through the design of actions like blowing long or short, gently or quickly.

### Breathing in Virtual Reality

Relatively few prior works employ breathing in VR experiences. Mapping inhalation and exhalation to movement was first integrated in VR by Davies and Harrison [8]. A recently developed VR scuba diving experience used breathing, detected by a gas sensor attached to a snorkel, such that the player could inhale to ascend and exhale to descend in the simulated underwater world [16]. Soyka et al. [35] combined an underwater VR experience with breathing techniques for stress management. Similar immersive experiences could encourage specific types of breathing techniques (e.g., deep long breaths) for promoting wellbeing. A meditation VR experience used breathing rate as indirectly controlled input to change the VR environment [27]. None of the previous works have employed breathing as an active input mechanism. We propose our directly controlled breathing actions as a novel way to broaden the input channel in VR games.

## DESIGN

### Control Action Design

We propose four intuitive active breath control actions as additional input channels in the game:

- *gale*, is strong and sustained blowing out (imagine a dragon breathing out fire or someone blowing out candles on a birthday cake)
- *waft*, is air blown out slowly for a short duration with an open mouth (like blowing on a window to fog up the surface)
- *gust*, is a transient but strong jet of air blown from the mouth (similar to blowing dust away from objects)
- *calm*, is a temporary decline in breathing rate to zero (holding your breath)

The left image in Fig 1 shows a schematic of our breathing actions. *Gale* and *calm* are continuous actions and their effect depends on how long the player can sustain the action. Players can control the duration of the effect by controlling the duration of the action. *Waft* and *gust* are instantaneous. Once the player does the action, it immediately triggers an effect.

From an informal poll at our lab, we chose four out of seven breathing actions that most people preferred. We explored three different sensors (microphone, temperature sensor, Zephyr BioHarness[1]) to find one that could detect them all. Both the microphone and the temperature sensor worked well for detecting blowing out related actions, but were not stable enough for inhalation related actions. With the Zephyr

[1]https://www.zephyranywhere.com/

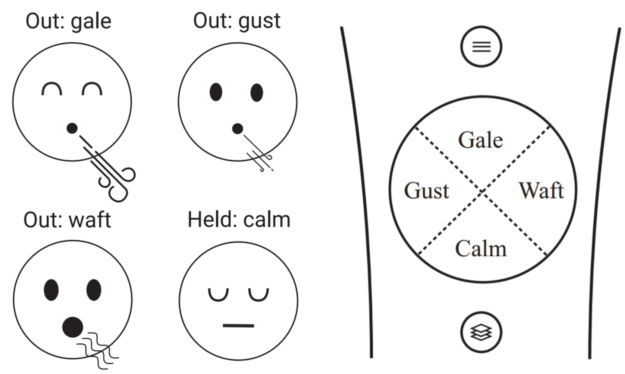
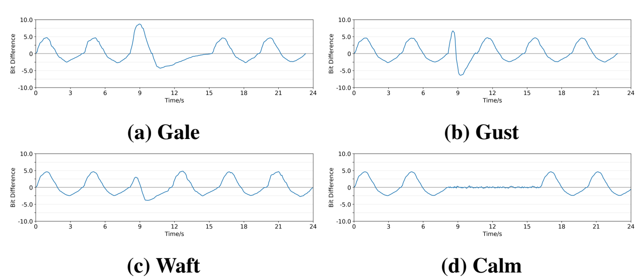



**Figure 1: Left: The four breathing actions. Right: Actions mapped to four areas on the HTC Vive controller trackpad.**

we were able to detect both inhalation and blowing out actions robustly. We first collected several samples of each breathing actions as the baseline. During gameplay, we used zero-crossing points of the raw waveform's first order difference (from Zephyr) as the markers for every breath cycle and employed fast dynamic time warping to detect the most similar breathing actions. *Calm* was detected by its extraordinarily high zero-crossing rate.For the user study, we included a backup keyboard based effect trigger for those instances when detection failed. This was engaged by the experimenter, when needed, to maintain smooth gameplay experience for the participants. The Zephyr sensor communicates with the VR system via bluetooth. To reduce noise in the data we asked players to not twist their torso when doing the breathing actions.

Figure 2 shows the first order difference of the raw waveform received from Zephyr with one author performing the four actions. The actions are easily recognizable with an average recognition accuracy of 88.3 percent in a pilot study with two authors. The average recognition time lags are 504 ms for *gale*, 359 ms for *gust*, 298 ms for *waft* and 447 ms for *calm*. In the user study, if a action failed to be recognized, instead of interrupting the user's experience or causing confusion due to its failure, we injected the expected game effect with a key press. This was transparent to the user and helped maintain continuity of the play experience, necessary for the evaluation of the breathing action design.



(a) Gale (b) Gust

(c) Waft (d) Calm

**Figure 2: First order difference of the raw waveform from Zephyr**

### Control Button Mapping

We designed four breathing actions and assigned an ability to each action per game. In order to compare the novel breathing actions with conventional handheld controller input in the user study, we mapped the same abilities to four areas on the controller trackpad (see Fig 1 right). The player can activate continuous actions (*gale and calm*) by pressing down and holding the respective areas on the trackpad. The discrete abilities (*gale and waft*) are activated when the player simply presses down on the respective areas of the trackpad.

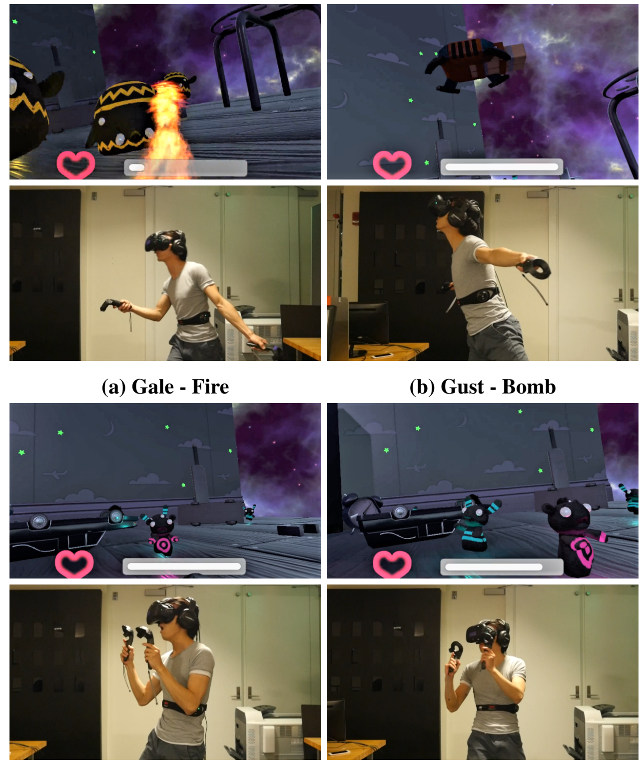
### Game Experience Design

We organically integrate the breathing actions into a single-player first person shooting (FPS) game and a two-player ball game. We chose these two games because they are both easy and fast to learn how to play. All the actions are designed to actively affect the gameplay. The effects mapped to each breathing action are inspired by common gameplay mechanics in video games.

#### *FPS Game*

The game story places the player in a parallel world of giants. In this world there are zombie-like toys that attack the player and survival depends on killing the continuous wave of enemies before getting killed. The player wears a special band around their chest (the respiration sensor) that gives them "superpowers" to help in their fight. The band also maintains the player's corporeal form and gives them the ability to fight as long as they stay within a small area (the tracking area). When the game starts, an endless stream of zombie-like enemies begin spawning at increasingly higher rates in the distance and walking towards the player. The more enemies that get killed, the faster new ones spawn. It is an endless game and the goal is to survive as long as possible and to obtain a score as high as possible.

Shooting is achieved by pressing triggers on the hand controllers Beyond this, the player can use four breathing actions as "superpowers" to prolong their survival by either causing higher damage to multiple enemies or changing enemy movement. *Gale* triggers fire breathing, which causes more damage than bullets The fire sustains until the player stops blowing out (see Figure 3a). *Gust* is mapped to "spitting" out a bomb in the direction where the player is facing (see Figure 3b). The bomb causes an 'area of effect' damage by killing all enemies within a certain fixed radius *Waft* produces an icy effect freezing all enemies for five seconds, making it easier to kill them without being overwhelmed (see Figure 3c). *Calm* makes the player go into stealth mode by becoming invisible which confuses the enemies, causing them to lose the player as their target and wander around aimlessly (see Figure 3d). This gives the player extra time to use other abilities, especially when the enemy spawn rate is high. The effect ends when the player resumes breathing. Figure 3 shows the user performing all four actions with their corresponding effects in the game. As a commonly used game design feature, each "superpower" has its own cooldown time which is the time interval before the action can be triggered again. This is done to prevent the use of an ability in rapid succession.



**(a) Gale - Fire** **(b) Gust - Bomb**

**(c) Waft - Freeze** **(d) Calm - Stealth**

**Figure 3: Breathing actions and corresponding effects in the FPS game.**

The score and cooldown timers for each ability are displayed on the bottom of an upturned toy car in the game world (see Figure 5a). The player can easily turn to the car to check their score and to see how long they need to wait until a particular action becomes available again.

#### *Ball Game*

The setup is a ball game competition on a spaceship with low gravity. Two players stand at opposite ends of a $16m$ corridor and a ball is alternatively placed in front of the players at the start of each round. Players wear a chest band which adds gravity and keeps them upright and stable for the competition along with giving them new abilities (the respiration sensor). Players act as goalkeepers defending their gates located behind them while doing their utmost to shoot the ball into their opponent's gate. The gravity band only works in a small area and hence player movements are limited to this rectangular space (the tracking area).

There are several approaches for players to change the movement and direction of the ball. Pushing or blocking it with their hands is one method. Since players hold a controller in each hand and the controller positions are tracked by the Vive tracking system, interacting with the ball using their hands is easy and natural. Another option is to use breathing actions that are mapped to abilities for controlling the ball's movement, especially when the ball is beyond arms reach or moving too fast. *Gale* applies a constant force on the ball, in the direction where the action initiating player is facing. Force is

**(a) Gale - Force** **(b) Gust - Turn**

**(c) Waft - Stop** **(d) Calm - Slow**

**Figure 4: Breathing actions and corresponding effects in the ball game.**

applied on the ball as long as the player keeps blowing (see Figure 4a). Gale works as a force that either pushes things into the wind or slows things down that are going against the wind. *Gust* changes the ball's direction to where the player is facing, and the ball moves with the same speed as it did before being turned (see Figure 4b). *Waft* freezes and stops the ball immediately. This effect does not have a duration. The ball needs to be moved by either player using another action (see Figure 4c). *Calm* slows down the ball (see Figure 4d) with an exponential decay in velocity (the velocity value is multiplied by 0.99 every 10 milliseconds). The effect stays as long as the player holds their breath and ends as soon as normal breathing is resumed or another action is initiated. Figure 4 shows the user performing all four actions along with the corresponding effects in the game. Similar to the FPS game, all actions have cooldown times.

A scoreboard is suspended from the ceiling in front of each player, which shows them their own score, the opponent's score, and the cooldown time for each action (see Figure 5b). Players can only see the cooldown times of their own actions.

## EVALUATION

### Participants

We invited 16 volunteers (4 females, average age 26.8, with SD 5.8) to test the two VR games. Participants were paired in groups of two (eight groups) based on their registered time slots. Seven of them did not have any prior VR experience, other than viewing 360 video with devices like the Google Cardboard. Nine participants were non-video gamers.

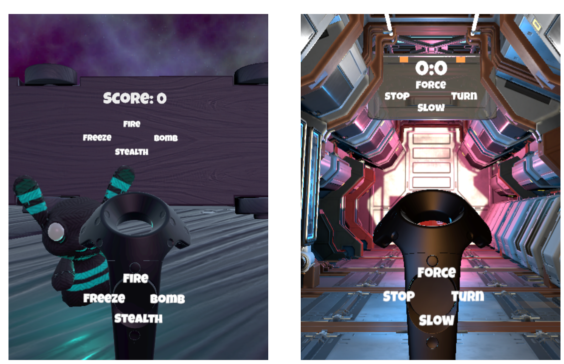
### Apparatus

We used two separate HTC Vive setups during the study, each connected to a desktop PC. The two setups were placed around the corner from each other due to the layout of our lab space such that players could hear but not see each other. The tracking area was setup for standing experiences and limited to 1.5m $\times$ 2m for each game. Two games were built with Unity. The FPS game was built on top of the Unity Survival Shooter tutorialand the ball game was set in the 3D environment downloaded with the Sci-Fi Laboratory Pack 2, both available on the Unity Asset Store. The two-player ball game used Unity's built-in networking system. To reduce network latency, the PCs were connected to a LAN with ethernet cables.

### Experiment Design

To compare our breathing actions with controller based input, we used a within-subjects design. All participants played both games twice, once with breathing actions and once with controller input. For non-breathing controller input, the abilities were mapped to four cardinal areas on the controller trackpad in both games (see Figure 5).

Two participants were scheduled for each study session. They experienced the FPS game individually and played the ball game together. To minimize any play order effect, half of the pairs played FPS first while the other half started with the ball game. In each pair, one participant played the game with breathing actions first and the other started with controller input and this was counter balanced across all participants and games. Overall each participant played four times during the study, playing each game with and without breathing actions. In order to maintain a constant degree of exposure to the games and actions, the duration of each game trial was set to 5 minutes. After each trial, participants were asked to complete a questionnaire ($Q_1$) about their play experience. When participants finished both conditions (breathing and non-breathing controller input) for one game, they were asked to fill a final questionnaire ($Q_2$) that compared the




**(a) FPS game abilities.** **(b) Ball game abilities.**

**Figure 5: Scoreboards for each game visible in the background. Foreground shows "superpowers" on the hand controller's trackpad as seen by the player in each game.**

| | FPS Game | | | Ball Game | | |
|---|---|---|---|---|---|---|
| | Breathing | Non-breathing | Wilcoxon Test | Breathing | Non-breathing | Wilcoxon Test |
| Individual Presence | $2.3 \pm 1.2$ | $0.9 \pm 1.0$ | $V = 66.0, p^{**} = 0.004$ | $1.1 \pm 1.1$ | $0.6 \pm 0.8$ | $V = 8.0, p^{*} = 0.015$ |
| Social Presence | – | – | – | $3.3 \pm 1.6$ | $3.1 \pm 1.8$ | $V = 31.0, p = 0.536$ |
| Feeling of Fun | $6.6 \pm 0.6$ | $6.1 \pm 0.8$ | $V = 21.0, p^{*} = 0.031$ | $6.4 \pm 0.8$ | $5.6 \pm 1.1$ | $V = 58.0, p^{*} = 0.025$ |
| Feeling of Challenge | $5.9 \pm 0.9$ | $5.0 \pm 1.0$ | $V = 73.0, p^{*} = 0.006$ | $5.6 \pm 1.1$ | $5.6 \pm 1.2$ | $V = 20.0, p = 0.821$ |
| Feeling of Success | $5.6 \pm 1.4$ | $5.3 \pm 0.9$ | $V = 52.5, p = 0.295$ | $5.3 \pm 1.5$ | $4.8 \pm 1.4$ | $V = 50.5, p = 0.382$ |

* < 0.05, ** < 0.005, *** < 0.001

**Table 1: Mean scores of evaluation and results of a pairwise Wilcoxon Test between breathing and non-breathing controller based input.**

control mechanisms for that game. Overall each participant completed six questionnaires during the study session.

$Q_1$ for each trial was customized according to the game played and the control technique used. Except for one ranking question, all others were rated on a 7-point Likert Scale (1: Not at all - 7: A lot).

- Four presence questions from the Slater-Usoh-Steed (SUS) presence questionnaire [33]
- Five questions about togetherness [9, 17] (only for the two-player ball game)
- Three game experience questions from the Game Experience Questionnaire (GEQ) about fun, the extent of challenge, and the feeling of success [15]
- Three evaluation questions about the breathing actions (novelty, accessibility and usability) and one question asking users to rank the actions according to preference (only for sessions with breathing actions)

$Q_2$ asked three questions: user preference between breathing and non-breathing controller input, additional comments on the play experience, and additional comments on breathing control mechanisms. Questions were slightly modified according to the games.

### Procedure

The two HTC Vive stations were setup such that neither was visible from the other. Each station was managed by one experimenter. Before starting the session, participants were asked to sign a consent form. Experimenters introduced the game to be played (either FPS or ball game) and the corresponding actions (either breathing actions or non-breathing controller input) to each participant individually. On average a game trial plus questionnaire took approximately 10 minutes and the overall study lasted for about 50 minutes.

## RESULTS

### Presence

$Q_1$ includes four questions about presence. The score is calculated as the count of questions whose responses are 6 or 7 [33] and the score ranges from 0 to 4. Figure 6a shows the boxplot of 16 participants' scores for the four game trials respectively. A pairwise Wilcoxon test indicates that participants had significantly higher presence with breathing actions (see Table 1).

### Togetherness

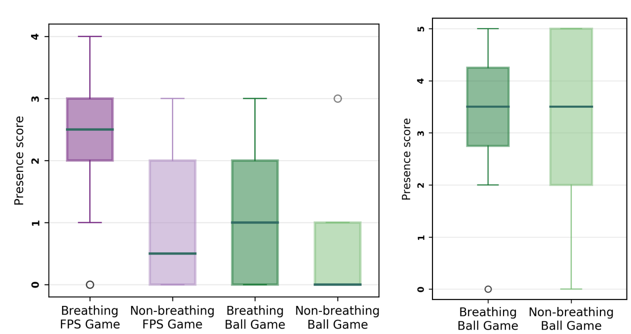
After each ball game trial, $Q_1$ asked an additional five questions on togetherness. A pairwise Wilcoxon test did not show any significant difference between the breathing and non-breathing conditions. Participants had similar togetherness scores for both input conditions (see Figure 6b).

### Game Experience

In both games, participants considered the trials with breathing actions more interesting. Since none of the participants rated fun less than 4, the y-axis of Figure 7 begins with 4. The results indicate that a majority of participants rated fun 7 on the $1-7$ Likert Scale for the breathing action game trials. A pairwise Wilcoxon test shows significantly higher fun score with breathing actions (see Table 1). When asked if they felt challenged, participants reported that in the FPS game, using breathing actions was more challenging than using controller input. This is most likely due to the fast pace of the game that necessitated frequent activation of breathing actions for survival. As for the feeling of success, there was no significant difference between the two input techniques in both games. The results are summarized in Table 1.

### Breathing Actions

A majority of the participants gave high ratings for breathing actions on novelty, accessibility and usability. Most participants rated the novelty of the breathing actions remarkably high (see Figure 8). In both games, all participants gave a score above 5 for novelty and 11 out of 16 participants rated it 7. This indicates that the breathing actions were sufficiently novel as an input technique. It seems likely the scores have taken into account the "novelty effect" of trying something




**(a) Individual presence.** **(b) Social presence.**

**Figure 6: Presence in both games.**

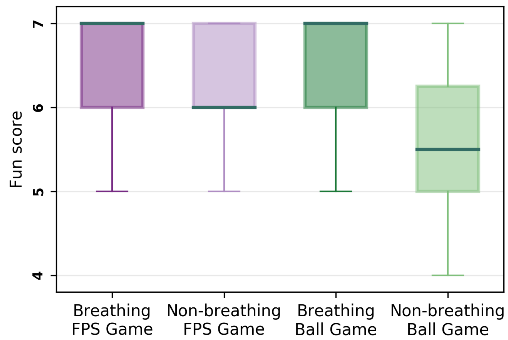



**Figure 7: Participant rating of fun in both games.**

for the first time since participants used breathing actions more than once. Accessibility and usability have comparatively fewer high scores. But only one or two participants out of 16 gave slightly lower scores. No participant rated any of the three aspects of the breathing actions below 3. Overall, the actions were favorably acknowledged by all the participants. It is difficult to determine whether novelty will wear off or not without doing a long term study. However, based on how player enthusiasm is session 4 matched that in session 1, we believe it may be a little while before the novelty wears off. We also believe that novelty usually wears off for any new VR or other experience, not just ours.

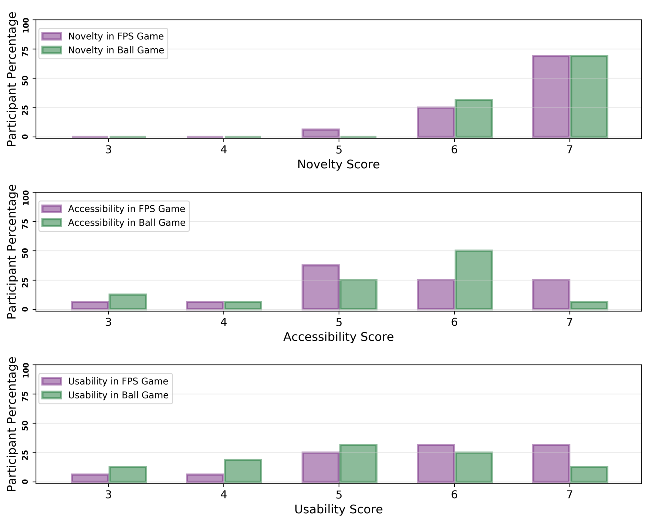



**Figure 8: Novelty, Accessibility and Usability for the breathing actions.**

The ranking results show that *gale*, the long and strong blowing action, is the most popular action (see Figure 9). In both games, more than 75% of the participants (13 out of 16) selected *gale* as their favorite action. Friedman test shows significant ranking differences between the four actions ($\chi^2_{3,FPS} = 16.5, p_{FPS} < 0.001, \chi^2_{3,ball} = 16.125, p_{ball} = 0.001$). Nemenyi test of mean rank sums indicates significant difference between pairs of *gale* and the other three actions, i.e., *gust*, *waft* and *calm*, but not between any pairs of the three actions. These results suggest that *gale* stood out among the four actions, while the other three were somewhat similarly preferred.

It is possible that *gale* was found familiar and easier to do and its mapping was found more intuitive leading to a preference bias. By the same token it could also mean that this action was well designed with a corresponding well designed effect. We believe that action preference was a function of who our participants were. For e.g., participants who were trumpet players or singers preferred *gale* while the swimmers preferred *calm* and used it repeatedly. The actions were introduced in the order "gale, gust, waft and calm."


**Figure 9: Ranking among Four Breathing Actions in Two Games**

When asked about their preference between breathing actions and controller input, at least 75% (13 out of 16 for the FPS game and 12 out of 16 for the ball game) of the participants chose breathing actions. We noticed an interesting effect of previous VR and video gameplay experience on player preference. Among the six participants who preferred controller input in at least one game, five had never tried VR before. According to whether a player had experienced VR or not, chi-square test showed significant difference in preference between experienced and inexperienced VR users ($\chi^2_1 = 6.1, p = 0.01 < 0.05$). Splitting participants based on previous gameplay experience, chi-square test showed a slightly significant difference in preference between experienced and inexperienced players. ($\chi^2_1 = 2.9, p = 0.09 < 0.1$). These results indicate that our breathing actions were more liked by experienced VR users and by video game players.

In the rest of this section, we describe strengths as well as shortcomings of the breathing actions derived from the analysis of participant feedback.

### *Natural Interaction using Breath*

"Intuitive" was mentioned eleven times in the comments from $Q_2$. Participants found it natural to use breathing to interact with the games, especially the *gale* action. *"I found the breathing interaction very intuitive. It enhanced the entire game experience"* (P9, FPS game). *"The breathing controls certainly made the experience more interactive and intuitive"* (P14, FPS game). Intuitiveness of actions can lead to increased usage thereby establishing a virtuous circle. *"I* *felt more encouraged to use the abilities through breathing than when they were controlled by button presses"* (P13, FPS game). Some participants emphasized their preference for *gale*. *"I found the force breathing control and ability to be very intuitive to use, particularly with the blowing graphic"* (P14, ball game). Two participants especially found the breathing actions natural and fun. They provided their experience as a trumpet player and an opera singer as the reason. The intuitiveness of *gale* might explain the overall high ranking for actions over controller input.

### Expansion of the Active Input Dimension

Several participants appreciated how breathing augmented the game controller input. *"The breathing allows for another added channels – feels more interactive"* (P8, FPS game). The actions being part of the human body's natural functionality can expand the game input dimension while retaining simplicity of interaction. *"The breathing mechanism as input is a really great idea to expand the forms of input for a game without increasing the complexity of the handheld controllers"* (P7, ball game).

### Stronger Feeling of Presence

In line with findings of significantly higher presence scores using breathing actions, some participants expressed feeling a greater sense of realism in the VR experience. *"Great fun game. Feel like you are being there with intense experience"* (P5, FPS game). *"The breathing interaction makes me feel like I am at the game more. Everything feels more real"* (P6, FPS game). *"The breathing interaction is great and fun. It makes the game feel real and make me feel like I am presented in the world more than just using the controller"* (P15, ball game). This may be explained by the intuitiveness of the actions, especially *gale*. Compared to the visual and proprioceptive connection between blowing out and seeing fire emerge from your virtual mouth, the disconnect between pressing down a trackpad button and seeing fire emerge from the virtual mouth likely impacted the presence scores for both input techniques.

### Connection between Physical and Virtual World

Another possible explanation for the increased sense of realism might lie in the connection between the real and the virtual world established through breathing. *"The breathing interaction made the game more fun – it felt more like a physical experience, rather than a purely virtual one"* (P14, ball game). Although immersed in the VR world, participants were still aware of the breathing actions they were doing. The visual and audio feedback in the game helped to link what they did and what they saw, and bridged the gap between the invisible physical world and the visible virtual environment. *"I preferred the breathing version because the breathing caused the abilities to feel more linked to my body and therefore more intuitive, as if it was an extension of myself"* (P6, ball game). Interestingly, this connection with reality did not decrease presence. On the contrary, players had more fun and felt an increased level of presence. *"I know what I was doing with my physical mouth and lung, but that in turn made me more immersed into the game, producing more fun during the gameplay"* (P1, FPS game).

### Fatigue from both Game and Actions

Participants who preferred non-breathing controller input predominantly mentioned fatigue as the reason. VR games are physically more demanding than screen-based games as the player is usually more active (standing or moving) during play. Interaction using handheld controllers also requires more body movement than using a keyboard or a standard game controller. The two games we designed demanded physical movement. Enemies spawning at increasingly higher rates required the player to shoot continuously and in all directions in the FPS game. Constant turning and moving along with arms held out for shooting can quickly get tiring. In the ball game, the players needed to not only be nimble for deflecting fast moving balls, they also needed to pay close attention to their opponent's behavior. Focus and speed along with twisting, turning, bending, reaching and other body movements can start to feel like a workout. Therefore, some participants found it difficult to add breath control into the already active mix. *"It's fun but more tiring and may be harder to execute compared to using controller."* (P11, FPS game). *"Quite fun, despite difficulty using the interactions sometimes"* (P12, FPS game). *"The breathing interaction ... might cause more physical tiresome from the game more than just a controller"* (P16, FPS game). *"It's harder and more tiring to use the breathing interaction although it's fun."* (P4, ball game). Note that almost all participants who liked the controller input (3 out of 3 for the FPS game and 3 out of 4 for the ball game) admitted that the breathing actions were interesting and fun, even though they induced a greater physical load. Some less intense games might be more suitable for the breathing actions, as suggested by one participant. *"I think that this mechanism works better for games that are less physically demanding"* (P16, ball game)

### Limitation of Memory Space

A potential issue with this unconventional interaction technique came from the difficulty of getting familiarized with all actions and their corresponding effects in each game. Although participants did comment that the breathing actions were intuitive, it was still hard for them to remember all the actions and their effects for both games in the short study session and game trial time. *"I started to forget what some of them were when the game got more hectic."* (P14, FPS game). We observed that some participants got comfortable with a subset of the actions and used those throughout the trial. We asked them for a reason and, *"I first thought the calm is not useful in the game, so that I totally forgot it after playing several minutes, though now I realize that it is actually very useful!"* (P7, ball game). *"At first I did remember all the actions, but after I used the first two and get quite familiar with them, I began to forget the rest."* (P5, FPS game). Although individual breathing actions are simple to perform, the problem might stem from the total number of actions as well as playing two completely different games with the same actions mapped to different though related effects. Having more learning time could help resolve this issue. Providing visual reminders about the action-effect mapping in the game or automatically providing suggestions to use a specific action during gameplay could also help reduce memory load.

*"Maybe it would be easier if there was a pre-game, where we can practice the breathing interaction on the ball and see how it works... it would be beneficial for people to interact with this sensor before going into game"* (P6, ball game). While we did use the first two minutes of each five minute session to familiarize players with the actions and game objectives, a longer learning phase would be more helpful.

## STRATEGIES FOR DESIGNING BREATHING ACTIONS

From the results of the study, participant feedback and our experience developing the system, we derive six guidelines which we consider essential when using breathing actions as input control mechanics in gameplay.

### Provide Narrative for Breath Gestures

In our games we described the main character, as someone who is trapped in a parallel world and has "superpowers" that help them survive, or someone in a spaceship with low gravity who is competing with an opponent and needs special abilities to help win the game. We also gave plausible reasons for the player to wear a sensor, either to retain corporeal form in the parallel world, or to stay grounded in the agravic spaceship. The "corporeal form" is an in-game story item that aims to make wearing the Zephyr sensor seem plausible to players. Playability [28] has been characterized by seven attributes. One of them is immersion which is the capacity of the video game contents to be believable, such that the player becomes directly involved in the virtual game world. Our use of story for each game focuses on this attribute of playability to help put the player into the character's mindset and feel more fully immersed in the game. The narrative depicts breathing as the key to unlocking superpowers, which offers a believable reason for using the actions. This is essentially the first step of a two-step design process for integrating breathing actions as active and intuitive input control mechanisms. Only after users accept it can we further design appropriate effects in the game. Designers are encouraged to explore prior work on videogame narrative [18] to creatively explain the reasons for using breathing actions and for wearing a sensor. Besides our games, for example, a player can play as the fire-breathing dragon guarding its treasure. Breathing actions can be mapped to different attack abilities and the sensor can be described as the key to the dragon's transformation. Or, a player can fly a spaceship through an asteroid belt. Breathing can be used to either move or destroy the asteroids and the sensor band can be the connector between the different control units distributed around the spaceship.

### Relevance of Game Effects to Breathing Actions

A suitable game effect is the second step in making a breathing action feel intuitive. *Gale* triggers fire-breathing in the FPS game or a wind force in the ball game. The effects visualized as fire and wind match the users' expectations of what constant blowing might logically do in each game. This match can further impress upon the users the reasonableness of the action. Given the fire and wind effects, *gale* was shown to be an extremely intuitive and winning breathing action. The other three actions were comparatively less intuitive and showed more variance on users' preference. Pertinent audio feedback is as important as the visual effect to connect the physical world action with the virtual world effect. Taking *gale* as an example again, fire or wind effects in each game originate from slightly below the HMD camera position (user's eyes) with the appropriate spatial sound effects. The effect's position and sound make it seem like its coming out of the player's mouth. This helps bridge the users' expectation of releasing air when blowing out with corresponding feedback from the virtual environment [2], leading to a stronger feeling of realism and higher sense of presence.

Designers should think carefully about proposing favorable effects that are suitable for their designed actions. For example, using *gust* to blow on a virtual dandelion in an outdoors experience or on an old dusty book jacket in a fantasy game. Playful interactions like blowing bubbles or blowing out candles can be easily integrated into a VR experience. Wind instrument players or singers (choir, opera, or pop) may benefit from training games that employ relevant breathing techniques. It is possible to successfully use the same actions across multiple games when the mapping between the action and its effect is conceptually similar, for e.g., *gale* for fire-breathing and wind force in the FPS and ball games respectively. Conversely, it might be difficult to find natural mappings for a action or multiple mappings may exist. Natural mappings provide an intuitive game interface but can reduce flexibility by limiting a action to one effect, requiring a large number of actions to be designed. Multiple mappings allow the use of a single action for doing different things in a game, but can be confusing or difficult to remember. For designing multiple mappings that are easy to remember, the effects for a action should be similar (blowing out fire or wind, blowing away bubbles or dandelions) or exact opposites (freezing or melting, rising or falling). Which effect happens when a action is used can be dictated by the game situation, where either the action naturally makes sense (blowing out a candle) or the user has the ability to choose the effect.

### Manage Suitable Physiological Load

From participant feedback and observations we learned that fatigue from overuse can adversely impact the usage of breathing actions. While most participants found breathing actions fun and interesting, some still preferred the hand controller for input and used breathing sparingly. Designers should take into consideration prior gaming experience as that may dictate controller preference and gameplay style. Breathing actions are not an efficient input technique for "twitch gameplay" where reaction time for attack or counter attack is a decisive factor. Thus, the type of game being designed should dictate whether or not to use breathing actions. The FPS game gets progressively harder with frequent and faster enemies making it difficult to use the actions later in the game compared to the beginning of the game. Game designers need to balance gameplay and difficulty with physiological, physical or cognitive load. A general rule is that the more active and faster the game, the less frequent would be breathing action usage for most participants. However, some participants may overuse a action and breathe too quickly which could lead to hyperventilation or hold their breath too long which could cause dizziness. Managing the pacing of the actions through cooldowns and providing a training session are two ways to mitigate overuse. Another option is to automatically manage the intensity of the game to adjust to user action usage, for e.g., controlling the number and walking speed of the enemies in FPS and changing the moving speed of the ball in the ball game. Yet another approach is to provide a positive feedback loop through the game that discourages fast breathing [25] or any action that may be overused. Guided action usage where the game tells a player when to use a particular action can be a simple approach to resolving excessive usage. Designers need to keep extreme user behaviors in mind while creating actions and provide some inbuilt safety features.

### Provide a Good Tutorial

There is the potential problem of remembering actions and their corresponding effects. For some actions, the mapping is more intuitive than others, as shown in the study, but that may not be the case for every action. Thus, including a tutorial with an instructor that shows players how to interact using actions and controls, what the game objectives are, and how the world reacts to their input would improve player experience. Previous research has shown that a docent can improve player experience in virtual reality [26, 39]. Additionally, displaying the mapping of a action to its effect in the scene could provide a helpful reminder whenever needed, especially if a single action is mapped to multiple effects. .

### Customize Breathing Actions for Different Abilities

Users have different levels of tolerance induced by the physiological load of breathing actions, as well as different preferences on the usage frequency and type of actions based on prior experiences. For example, some users may find it tiring to use a action every twenty seconds while others may find the twenty second cooldown time too long. Some users may consider four actions too few while others may find it difficult to remember them. Or some may prefer *gale* and *gust* while others may like *gale* and *calm*. In our study, a swimmer preferred *calm* over other breathing actions while a trumpet player preferred *gale*. Designers should be mindful of player preferences and consider the added flexibility of a action customization system. Such a system could allow users to choose the level of breathing load (e.g., low, high) and the number and type of actions at the start similar to selecting a difficulty level commonly seen in existing games.

## LIMITATIONS AND FUTURE WORK

In this paper we have shown that breathing actions can create exciting and immersive gameplay experiences. Breathing has three essential "forms", i.e., inhalation, exhalation and hold. To cover the entire gradient of possibilities for all three breathing forms, newer actions need to be designed and tested. We focused on four actions that are relatively simple and familiar based on people's everyday experiences. More research on different action mappings needs to be conducted to fully understand the dynamics of direct physiological control in active VR games. Our actions use the latter two forms (*gale*, *gust* and *waft* use exhalation and *calm* uses hold), but not inhalation. Actions based on different types of intake like suction may be suitable for controlling things in the virtual world like pulling objects towards the players.

Action duration is partially explored in our design. *Gale* and *gust* are both blowing out actions that vary in duration. The same idea can be extended to a long or short suction. Strength is related to duration – the harder you breathe in or blow out, the shorter duration you can do it for – and it also has its own unique components of blowing strongly or softly. All these can be easily performed by players. To access these dimensions, microphones, temperature, humidity or air-flow sensors could be employed. Compared to the Zephyr, a wearable air-flow sensor may have advantages in distinguishing different strength levels. As for mouth-shape, designers may need to resort to a microphone to detect the exhalation sounds. For instance, two additional actions can be proposed: *hiss*, when a user grins and blows air out through their teeth and make the "sss" sound; *shhh*, when a user puckers up their mouth and blows out making the "shh" sound. These two actions have similar diaphragm movements as *waft* but different sounds which would be more easily distinguishable using a microphone than the Zephyr.

We need to further explore the performance differences between games with and without breathing actions. We also need exploration into the types of games that will benefit from direct controls especially keeping player fatigue in mind. To help manage the number of actions, it may be useful to create 'combos' where a action has one effect when used by itself but has a different effect when used in combination with a button press. Button combos are commonly used for mapping different abilities in screen-based games and are worth exploring for natural input techniques as well. Playing with others can lead to greater enjoyment and thus, we plan designing and testing asymmetric gameplay experiences with breathing actions where VR players can play with non-VR PC, phone, or tablet players.

Both our games had no end condition. While test participants played each game for five minutes, some players died well before the five minute point while others kept going, which made it difficult to do a valid within-subject comparison. Quantifying gameplay in terms of enemies killed or lives lost is worth considering for future work.

## CONCLUSION

In this work we presented breathing as a directly controlled input technique for VR games. We designed and implemented four breathing actions and two game experiences that explore different natural mappings of the actions to effects in the virtual world. Analysis of results from a study with 16 participants provided us with more insights into the pros and cons of using breathing actions. We further identified six design strategies for VR game designers interested in adding breathing actions to their games. As VR becomes broadly accepted and new forms of input emerge, we need to consider player needs to balance interaction using traditional input methods like keyboards or controllers with newer immersive physiological inputs.

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