Attending to Breath: Exploring how the cues in a virtual environment guide the attention to breath and shape the quality of experience to support mindfulness

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ABSTRACT

Busy daily lives and ongoing distractions often make people feel disconnected from their bodies and experiences. Guided attention to self can alleviate this disconnect as in focused-attention meditation, in which breathing often constitutes the primary object on which to focus attention. In this context, sustained breath awareness plays a crucial role in the emergence of the meditation experience. We designed an immersive virtual environment (iVE) with a generative soundtrack that supports sustained attention on breathing by employing the users' breathing in interaction. Both sounds and visuals are directly mapped to the user's breathing patterns, thus bringing the awareness researched. We conducted micro-phenomenology interviews to unfold the process in which breath awareness can be induced and sustained in this environment. The findings revealed the mechanisms by which audio and visual cues in VR can elicit and foster breath-awareness, and unfolded the nuances of this process through subjective experiences of the study participants. Finally, the results emphasize the important role that a sense of agency and control have in shaping the overall quality of the experience. This can in turn inform the design specifications of future mindfulness-based designs focused on breath awareness.

ACM Classification Keywords

H.5.1. Information Interfaces and Presentation (e.g. HCI): Multimedia Information Systems – Artificial, augmented, and virtual realities

DIS'18, June 9–13, 2018, Hong Kong

ISBN 123-4567-24-567/08/06. . . $15.00

DOI: https://doi.org/10.1145/3196709.3196765

Author Keywords

Mindfulness; Breath Awareness; Virtual Reality; Immersion; Well-Being; Embodiment.

INTRODUCTION

An increasing amount of our daily interactions in the world are mediated by digital technologies. With the rise of ubiquitous computing, an increasing number of our actions are measured, stored and quantified. Smart-phones and wearable technologies track our location, social interactions, and physical activity. The rise of these technologies for the 'quantified self' [77] often focuses on increasing our productivity by tightly monitoring our actions in the world. However, the more we focus on these outward uses of technology, the less we experience an embodied self [70]. Yet, there are opportunities beyond quantification. By designing technologies "as experiences" [40] and by minimizing distractions and bringing focus on the self, we can move toward improving the quality of our interactions and quality of life [5].

In this context, a growing thread of HCI research investigates how embodied approaches to interaction design can support an increased attention to the self [60, 22]. From this body of work, we have focused on designs built upon the concept of *mindfulness*, defined as "the awareness that emerges through paying attention on purpose, in the present moment, and non-judgmentally to the unfolding of experience moment by moment" [26]. Our work builds upon *mindfulness-based design* evolving around the practice of *focused-attention meditation* (FAM) [33]. FAM is a practice of sustaining focused attention on one, "primary", object of attention (internal, such as breathing, or external, such as a candle light). Focused attention on breathing is a widely accepted practice that aims at cultivating a sense of being present with a demonstrated impact on well-being. Engaging in breathing exercises influence cognition, memory, and emotional processing [24, 79, 51], and decreases anxiety and stress [24], even in a young population [30].

A large number of mindfulness-based designs are built upon nuances of FAM with a focus on breathing. Mindfulness-based design can be used to guide a user's attention to breath, for example through Virtual Environments (VEs) that employ breathing cues [64, 52]. Despite a significant number of mindfulness-based designs that guide the attention to breath, our understanding of how breath awareness is elicited and how the design of VEs can sustain the user's attention on breath are still limited. This is what motivates the research effort presented here.

In this paper, we investigate how a continuous interaction between breathing patterns and a virtual environment can induce and support the breath awareness of users. Our inquiry is motivated by the preliminary findings in [54] that showed the potential of the VE and interaction design to elicit and sustain the user's awareness of their breathing. Hence, our goal in this study is to better understand (1) how the users of the *Pulse Breath Water* system become aware of their breathing in a VE without verbal guidance during the interaction, (2) how the cues in the VE can support sustained attention on breathing, and (3) gain a deeper understanding of the actual experience of becoming aware and sustained awareness of one's breath. To answer these research questions we (1) built the *Pulse Breath Water* system, and (2) propose an empirical qualitative study employing micro-phenomenology interviews [50].

BACKGROUND

Mindfulness-Based Design

The third wave in HCI [4] brought the embodied approach to interaction [11] to the forefront by acknowledging the importance of the embodied experience in sense-making of the experience. A number of design approaches position the body at the center of a user's experience. For instance, *Somaesthetics* designs cultivate an aesthetic appreciation of bodily experience [62, 59]. *Somaesthetic Appreciation design* gives rise to the experience through guided attention inwards, to the self; excluding external distractions and making space for somatic awareness to arise [23]. Yet another concept, *Somatic Connoisseurship*, demonstrates how "body-based awareness skills" can be utilized in experience design and designing for the experience of the self, by building upon somatic phenomenology and first-person practices for self-awareness [61].

The designs we focus on are built upon mindfulness principles and encourage a shift of attention inwards, towards bodily sensations, in order to support well-being and self-regulation processes [3]. Mindfulness has been defined as a state of being non-judgmental and present in the moment-to-moment unfolding of the experience [26]. Mindfulness-based designs aim to bring one to the state of mindfulness through various approaches. For example, Zhu et al. [80] recognized four approaches to designing for mindfulness: *Digitalized mindfulness* that is a digital equivalent to guided meditation; *Personalized mindfulness* that addresses personal preferences regarding mindful meditation; *Quantified mindfulness* that is built upon applications that offer real-time sensing and feedback; and *Presence-in and Presence-with* approach that goes beyond tools and offers a way of mindful being rather than doing.

The most common mindfulness-based designs take the form of a mobile application [8] that tackle mindfulness from different angles: mobile applications that guide a user to distance itself from troubling thoughts [78, 47], foster mindful walking through ambient sound generated from walking and breathing patterns [7], applications that serve as mindfulness meditation timers [48], applications for didactic guided meditation sessions [69], or applications that integrate mindfulness principles within a broader framework such as *acceptance and commitment therapy* [1]. Beside mobile and computer applications, mindfulness-based designs have taken on the form of audio installations - *Sonic Cradle* [73, 74], virtual environments [41] - *The Meditation Chamber* [64], *RelaWorld* [32], *Sanctuarium* [12], *PsychicVR* [2] and more recently, mixed reality environments - *Inner Garden* [58].

Focused-Attention Meditation

Mindfulness practices encompass various approaches to bringing the user's awareness to the present moment. A growing number of mindfulness-based designs revolve around the practice of focused-attention meditation (FAM) [37, 38]. In FAM a practitioner shifts their attention from external stressors to internal sensations such as breathing [55], and is considered the most widely accessible practice among novice meditators [38]. Practicing sustained focused attention on breath has been shown to reduce stress and improve well-being [31]. Most importantly, FAM fosters interoceptive awareness, an ability to receive and attend to the signals originating in our bodies [14, 21], which is shown to not only improve attention task performance but as well contribute to emotion regulation [10, 44].

Designs for Breath Awareness

How can we support the meditation community with technology [9] is an open-end question that is explored within the HCI community from many different angles. We focus on designs that "facilitate mindful moments" of being present and self-aware by directing the user's attention to their breathing [55]. We review systems using multi-sensory feedback to support mindful reflection, by "bringing unconscious aspects of experience to conscious awareness" [63]: p.50. Many designs for breath awareness have been proposed in HCI [66]. *Sonic Cradle* [73] was designed for cultivating mindfulness through a soundscape in which sounds are triggered by breathing. *BrightBeat* [18] was designed for cultivating calmness and focus through utilizing screen brightness with breathing patterns and audio feedback to guide a user towards intended breathing. *SomaMat and Breathing Light* demonstrated a different approach to mindfulness through breathing by emphasizing breath-related somaesthetic qualities through light and heat feedback [67].

Specifically, we focus on Virtual Reality (VR) as an "embodied technology" that can support the user's attention to bodily sensations using the sense of immersion and presence [56]. By employing audio-visual cues to breath as another representation cue, VR can provide a sensory-augmentation dimension that supports the user in focusing attention on breath. Because immersion in VEs minimizes external distractions, VR is a promising medium to support mindfulness practice and elicit breath awareness [65, 55].

Different approaches to designing for breath awareness and FAM in virtual reality have been proposed. In *Solar* [52], breathing and electroencephalography (EEG) data are mapped to the elements in the virtual environment that provides audio and visual cues and is presented on a desktop screen. *Guided Meditation VR* [42] and *JunoVR* [75] immerse the user in a VEs that resemble nature and uses audio instructions to guide the user's attention to breathing. Similarly, abstracted natural environments are used as a design element in: *Lumen* [43] that employs guided meditation and gaze interaction for navigation through an enchanted forest; *Life Tree* in which the growth and liveness of the tree are controlled by the user's breathing rhythm [49], and in *Deep* which depicts an underwater fantasy world which the user navigates by deepening their breathing and adjusting to a slow pace [71]. Other applications employ continuous – and potentially ambiguous – feedback to guide the users' attention. The *Meditation Chamber* [64], provides biofeedback in a VE using multimodal data – breathing, electrodermal activity (EDA), and blood volume pressure – along with guided instructions, and presented on HMD. Similarly, in *Strata*, breathing, heart rate, EDA, and brain activity determine the visuals and the audio of the virtual environment depicting five different worlds unified into a single experience [13].

However, while some of these applications are built upon the gamification paradigm [25], and often include guided meditation as an invite to the experience, our interest is in the experiences that can guide user's attention to breathing through the cues in the environment. Therefore, our approach does not involve any guided meditation instructions, nor have we intended for our VE design to be a game. Our focus is on VR applications presented on immersive HMD and without verbal guidance into the practice. Hence, we designed *Pulse Breath Water* as a generative environment in which the events are determined by breathing pattens and the system's decision (by AI agent), where the user's breathing is employed as one and only modality for the cues in the iVE.

Despite a significant number of mindfulness-based VEs that support breath awareness, there is still a lack of a deeper understanding of how specifically breath awareness is elicited through different cues and interactions in VR. In this work, we aim to get a detailed understanding of user experiences of a particular design using micro-phenomenology interviews. Our design employs breathing data in a continuous audio and visual feedback in the virtual environment. The complexity of the visual elements is kept minimal to minimize dispersion of attention. The immersiveness of the medium contributes to decreased external distractions and an ability to elicit body sensations and direct attention towards one's breath, supported by generative audio that responds in real time to the changes in breathing patterns.

Micro-Phenomenology: A Methodology for the Study of Experience

To understand the subjective experiences of the participants, we chose *micro-phenomenology*, an inquiry method developed by Petitmengin [50, 45] upon Vermersch's *Explicitation interviews* technique [72]. The objective of micro-phenomenology is to obtain explicit descriptions of *singular experiences* as they unfold in a larger, chronological structure of the experience, bypassing generalized typical post-hoc descriptions.

For the descriptions of the experience to emerge in the interview, the interviewer and the interviewee use a precise communication-protocol as a tool for mediating the first-person point of view of the interviewee through the second-person position of the interviewer. The interviewee accesses the experience retrospectively following the guidance of the interviewer who takes a role of a mediator. The interviewer's role is to guide and stabilize the interviewee's attention, guide them through the process of evoking the experience, and then direct their attention to a particular dimension of the experience. Once the interviewee's attention is stabilized and they are in an *evocative state* – a state of re-living the experience – the interviewer guides the interviewee in deepening the description to the required level of precision.

Micro-phenomenology and *Explicitation interview* have been explored in HCI context in the past. Light [34] discussed the explicitation interview in the context of gathering experiences of using websites [34] and receiving mobile phone calls [35, 36]. Hogan [20] used the method to gather the users' experiences of data representation. Françoise et al. [15] utilized the method to evaluate the system they built for kinesthetic awareness while the same method was used by Candau et al. [6] to explore how interaction informed by somatic practices and embodied cognition contributes to cultivating kinesthetic awareness. To our knowledge, while the interest in micro-phenomenology to understand user experiences is growing, no published research has used the methodology in VR.

A VIRTUAL ENVIRONMENT DESIGNED TO SUPPORT BREATH AWARENESS

Pulse Breath Water system was initially created as an artwork [53] that evolved and doubled into a research instrument over time. We undertake a research-through-design [16] approach, and design iterations are informed by the exploratory studies we conduct.

Interaction Scenario

The main design premise is that the events in the virtual environment are determined by the breathing patterns. Deep slow breathing triggers slower, more sustained movement on the up/down-axis, allowing users to observe, reflect, and position in a particular part of the environment. Sustained breaths allow for staying in a place, while fast, strong breaths cause erratic movement. Metaphoric mapping [39] of movement allows for interaction that is easy to understand: on the participant's inhale, the position of the participant rises in the environment, and on the exhale they sink, just like when submerged in water. In our VE, the respiration data guides the audio generation in the affective space. The eventfulness of the audio is mapped to the appearance of the waves in the ocean. More eventful breathing generates more eventful audio that then generates a more disturbed ocean surface and increased waves. The element that depicts the passage of time is the sky that changes color from light gray to pitch black within a span of 6 minutes.

System design

Our design brings together three components: (1) A respiration sensor and respiration analysis module that drives (2) an immersive virtual environment (displayed on Oculus Rift SDK2), and (3) a generative sound environment. The novelty of the system, compared to other VR systems presented above, is in the generative audio and the AI agent that determines the events in the environment based on eventfulness of breathing that, to our best knowledge, have not been utilized so far in iVE.

The overall system outline is represented in Figure 1. One respiration sensor (Thought Technology) [76] attached to the user's abdominal area streams respiration data to M+M middleware [46] to MAX MSP [1] patch. The audio is generated by an autonomous agent that selects samples from the audio corpus according to the frequency of the user's breathing. All audio samples are tagged with different eventfulness properties using a state of the art music emotion recognition algorithm [68]. The overall eventfulness values of the audio environment is sent to the 3D game engine Unity 3D [2] along with respiration data via OSC messages. This data generates visual changes in the VE presented to the user via HMD. The user listens to the audio environment with circumaural noise-canceling headphones. A second respiration sensor was placed around the chest, and was used for data collection and as a reference, however chest data was not employed in the design.

Musical Agent: listening and responding through sound

Musical agents are artificial agents that automatize musical tasks. The hybrid musical agent generates the audio environment using the patterns of the user's breathing: slower subtle breathing triggers the agent to play less eventful sounds, and vice versa, faster deeper breaths result in the agent playing sounds that will be perceived as more eventful. The audio corpus contains piano recordings of musical chords that do not create musical tension and resolution. These recordings are further processed so that the origin of the recordings are not clear to the listeners. The recordings are all labeled with vectors with two dimensions: average pleasantness and average eventfulness based on Music Emotion Recognition algorithm [68]. Using Music Emotion Recognition, the agent maps the breathing to the eventfulness of audio samples to create an interactive sonic environment.

We apply signal processing to the respiration data using a wavelet transform. The wavelet transform outputs 24 frequency bands and these bands are mapped to the audio corpus' eventfulness range. The pleasantness range of the audio samples are substantially smaller than the range of eventfulness. The agent applies a random walk on the pleasantness dimension to create variations on the sample selection. The agent uses the generated eventfulness and pleasantness values to choose samples from the audio corpus. The selected sample is played by one of four playback engines of the agent.

In addition to piano sounds, a wave-table synthesizer [57] is used to generate a heartbeat-like sound controlled by the speed of user's breathing: the pulsation sound in the audio environment slows down as the user's breathing slows down. The interaction between the user and the audio environment is further enhanced by introducing a low-pass filter. As the user breaths in and out, the timbre of the audio environment oscillates between a muddy, low-frequency prominent audio environment and a full-spectrum audio environment. This also enhances the submersion feeling associated with being under the virtual water surface in the virtual environment (see section below *Virtual Environment: ART and Ambiguity of relationship as an invitation to the experience*).

Lastly, the agent applies Music Emotion Recognition algorithm to estimate the eventfulness and pleasantness of the generated sonic environment. The estimation algorithm is the online version of the estimation algorithm that is used to label the audio in the agent's memory. The output of online affect estimation is a vector with two dimensions: eventfulness and pleasantness. These values are further used to control the parameters of the virtual reality environment.

Virtual Environment: ART and Ambiguity of relationship as an invitation to the experience

Immersive environments can positively affect the user's attention, which was explained by Kaplan in *Attention Restoration Theory (ART)*[29]. ART focuses on the correlation between type of stimuli and restorative potential of nature environments [28]. The environments with stimuli that modestly capture attention are preferred over the stimuli that elicits mental fatigue and cognitive overload, and the design of our system relies on this principle. We used Unity 3D to generate the environment and 3D elements of a body of water - an ocean. The aesthetics of the scene is intentionally minimal, displaying the ocean and the sky in a range of gray-scale shades. The use of color is minimal. Design of elements in the VE is informed by the concept of *beholder's share* [27] in which the user's previous experiences guide the process of meaning-making of ambiguous stimuli. The ambiguity of visual stimulus encourages an interpretative relationship between a user and the environment [17]. In particular, *ambiguity of relationship* [17] between the user and the visual stimulus evokes users to project their values and experiences in reflection and meaning-making. For example, the ambiguous environment can be perceived as frightening and anxiety-inducing by one person or calm that elicits relaxation and peaceful feelings in other, building upon each person's previous real life experiences with real-life environments. Finally, continuous breathing patterns allow users to control the environment and curate their own experience.

Respiration data from an abdominal sensor controls the user's position in the environment. After initial testing, we decided to include movement on a vertical axis because the movement on a horizontal axis (along the ocean surface) was inducing motion-sickness. The mapping was informed by metaphoric mapping [39] built upon cognitive schema of "more is up, less is down (for example)". The more the participant breathes in, the higher in the VE they will go. We limited the height to which participants can move to prevent falling down from a high distance as that was reported as anxiety inducting by pilot participants. The eventfulness level is mapped to waves on the ocean surface: more eventful audio will cause more excited waves, and vice versa.

[1] https://cycling74.com
[2] Unity 3D: https://unity3d.com/

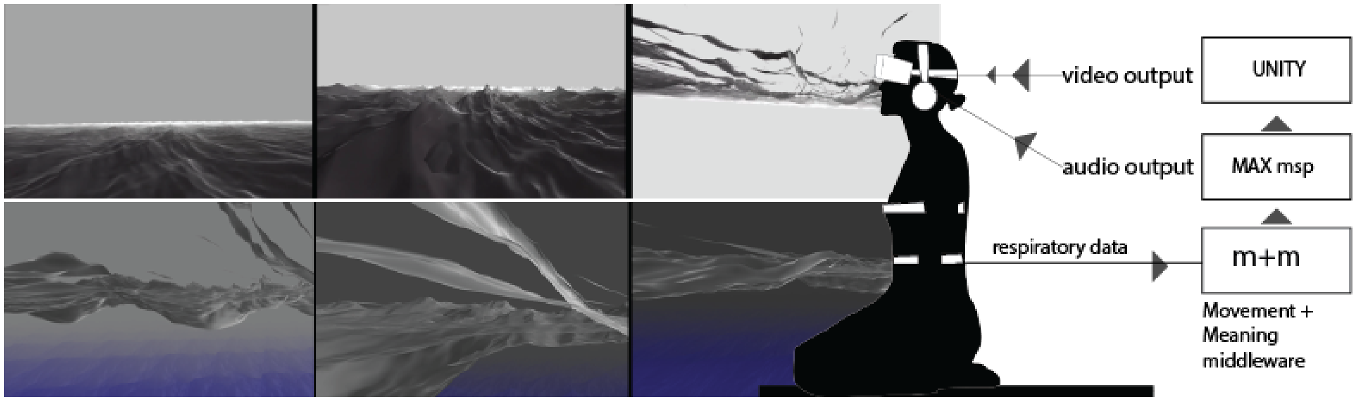

Figure 1. The system design

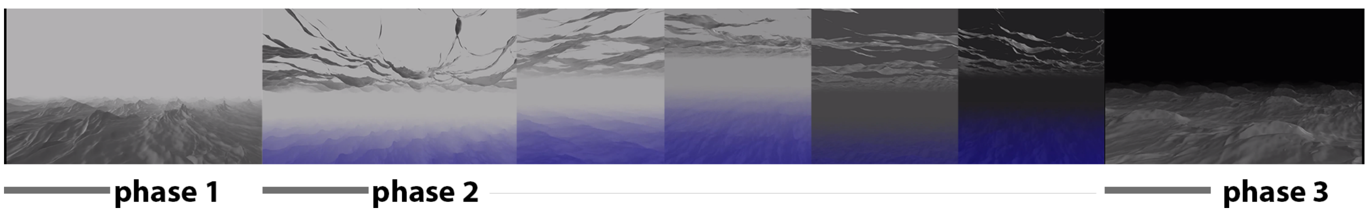

Figure 2. Duration: phase 1 (1 min) starts off with light gray sky and a stationary user's position above the ocean surface level; Phase 2 (4 min) is when the breath to movement mapping in the VE is activated and the user is moving along the vertical axis according to their breathing; the sky colour progresses from gray to black; Phase 3 (1 min)- the user is stationary again, and the only difference between this and phase 1 is in the colour of the sky

USER STUDY: UNDERSTANDING PERSONAL EXPERIENCES THROUGH MICRO-PHENOMENOLOGY

We conducted an exploratory study investigating how audio and visual cues mapped to breathing in the VE give rise and support to sustained breath awareness. The study aims to understand the experience of becoming aware of breath, and the nuances of the system that either support or distract a user in attending to self and becoming breath-aware. The participants were introduced to the VE following a four-part protocol described in more detail in Section *Protocol* (below). The insights are induced using micro-phenomenology interviews [50] after each completed session.

Artwork as a research instrument The initial design of our system was built upon the idea of a real-time generated piece, without narrative, end or beginning. To allow for gradual transition to and out of the environment that would enable us to inquire about the process of eliciting breath awareness, we iterated the system previously created as an artwork *Pulse Breath Water* [53] and added three phases. In the first and the last phase (phases 1 and 3) (see Figure 2), the user has a stationary position above the ocean and is presented with the cues of their agency through an audio environment. In the second phase, the user's agency is reflected not just through the audio (as in phase 1, and 3) but also their breathing controls the vertical position in the environment, moving the user above the ocean's surface with breath in and below the surface with breath out. The third phase is the same as the first phase, and the user is back to the starting position above the water while exposed to the cues of their breathing through the audio.

Designing 3 phases allowed for a variety of cues of the user's agency in the VE that could have influenced different mechanisms for eliciting breath awareness that we aimed to reveal in the interviews. The main points of interest were the switches between the phases in which the user's breath started impacting the environment (first reflected through audio cues in phase 1, then increasing the agency in phase 2 by adding movement cues, and then decreasing agency in phase 3 by presenting the audio cues only).

The length of the phases was determined in a pilot study conducted with 6 participants. The criteria was to find the balance between the time that seemed to keep the user's interest and flow state, and the point when the familiarity and lack of events in the environment becomes dull. Taking these pilot sessions into account, we reduced the length of the phases without agency as the users reported them as dull. Finally, the first phase is 60 seconds long, the second phase is 240 seconds long, and finally, the third phase is 60 seconds adding to the VE's duration to 6 minutes total (see Figure 2).

Participants

We recruited 11 participants (7 female) through the university mailing list and social media channels. Participants' ages ranged from 24 to 44 (mean: 27.1, SD: 5.87). Two participants had never tried VR before, eight participants had been exposed to it less than ten times overall, and one is an expert VR user. Regarding mindfulness practice, three participants meditate regularly, one has never meditated, and the rest meditate irregularly. All participants reported good health condition and normal vision.

Figure 3. The participant interacting with the VE, wearing breathing sensors, headphones, and Oculus Rift while seated on the cushion

Apparatus and Data collection
The participants were seated comfortably on a large bean bag pillow (see Figure 3), one at the time, in a dark room, at the computer station. The VE was presented on Oculus SDK2 at the rate of 90 FPS. The audio component of the VE was played on noise-canceling headphones. Participants wore respiration sensors (Thought technology [76]) positioned on the abdomen and chest and that data was captured. Also, interviews were audio and video recorded.

Protocol
Upon arrival, the participants read a description of the study. After agreeing to participate by signing the consent form, participants were equipped with two breathing sensors: abdominal and chest, and Oculus Rift, and the noise-canceling headphones. Prior to the sessions, we informed all participants that: "the virtual environment is reacting to your breathing" and we invited the participants to explore the experience without disclosing mapping details. The session was divided into four parts (see Figure 4):

1. *Session 1: Exploration*: The participants interacted with the virtual environment using their breathing for a duration of 6 minutes.

2. *Did the participant understand control and mapping details?*: After Session 1, we started interviews with all participants. Very early in these interviews we were able to determine whether participants made sense of the interaction and if they understood the correlation between the breath and the movement and sonic events in the environment (i.e., if they understood the mapping).

3. *Interview*: If they did, we would proceed to a full-length micro-phenomenology interview (this was the case with 3 participants [3]). If they did not make this connection (8 participants), they were instead invited to proceeded with Session 2 followed by the full-length interview.

[3]we will elaborate on this further in the Discussion section

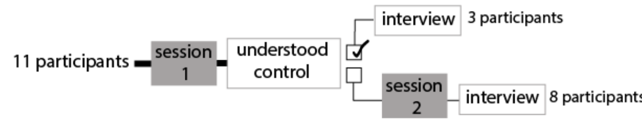

Figure 4. the illustration of the protocol

4. *Session 2: disclosed mapping details*: The 8 participants who did not make a sense of the control they had over the cues in the environment via their breathing, were explained the mapping details, that is how their breathing influences the virtual visual and sonic environment. Finally, they were asked to explore the environment again for another 6 minutes going through the 3 phases already described.

5. *Interview*: After the second session we conducted micro-phenomenology interviews, each 30 minutes in length.

Analysis
All interviews were transcribed and coded using the nVivo software for qualitative analysis. All interview data was structured in chronological order, and the descriptions of singular experiences were identified. The coding was done in two stages: first, interviews were coded line-by-line. Our coding system in this stage included the codes: control, attention, breath, body sensations, imagery, sound, feeling, inner voice, and were informed by six pilot interviews that we conducted prior to the study. In the second stage of coding, we identified common themes from the codes identified in the first stage of coding. Two researchers (the authors number 1 and 5), both trained in conducting micro-phenomenology interview, discussed and agreed on the themes.

FINDINGS
Unfolding the process of eliciting breath awareness
Attention shifts in becoming aware of breath
The complexity of the environment and the novelty of the experience can potentially be overwhelming to the participants. However, the three phases of the experience offered the possibility for a gradual transition of the focus from the environment to the bodily sensations related to the movement, and finally to the breath. Once aware of their control of the elements in the environment, a majority of the participants would direct attention first to the waves, the vertical movement patterns, and then to changes in the sonic environment, thus gradually discovering the nuances of the control they had over the environment, before starting to focus their awareness on their breathing. However, participants with meditation experience tended to immediately focus on the breath before shifting their attention to the environment, and finally to their bodily sensations:

> *At the very beginning I was focusing on my breath, just trying to listen and understand what was happening. And then the second part because I got the connection instead of listening to my own breath I changed my breath playing with the images and then I went to first state of listening to my body but I wasn't anxious anymore about motion sickness and the storms in the ocean and... I was focusing on really listening.* (P17)

Focused attention

Once familiarized with the environment, participants directed their attention to preferred parts in the experience by practicing controls they experientially learned during the session:

> *Initially I was repeating it, long breath in out in out but I didn't hold my breath even inside. After some time when it went on for some cycles then I started different things different rhythm of my breath as if I am controlling it. I was just trying to control that up and down... after that I realized [that] inside I'm feeling good, then I started staying inside.*(P14)

> *My focus is just I guess on the tranquility and lack of sharp noises and you know... how much air do I need to stay... like when should I take my next breath, and you know if I take my next breath is it going to be really deep breath.* (P9)

Finally when transitioning to phase 3 and losing the movement on a vertical axis, their attention shifted back to their body and "letting go":

> *OK, now I'm controlling my breath, and then with the white peaceful situation I attuned to my body and that was it, I wasn't controlling. I let that go...* (P17)

Cues in the VE for eliciting breath awareness

One of the most common difficulties for beginners in mindfulness breath FAM is attending to breathing without being distracted. In our design, this process was supported by the visual representation of breathing as a movement in the environment. As a matter of fact, participants were expected to first direct their attention outwards to the environment in order to be able to redirect it to the self. Their vertical position being controlled by how full their chest was simply allowed them to literally visualize their breathing, thus expliciting it.

> *I was more conscious of it [of breath] because of what I was seeing at the same time. [How did that make you conscious of breath?] I wasn't really concentrating only on my breath but also on what I saw... so I knew that I was breathing in but also by seeing where I was... or... at what point I was by seeing where I was.* (P10)

Figure 5 depicts the moment in which participant 17 became aware of the relationship between breath and the changes in the environment. The plot shows a change in their breathing pattern after the realization of their agency and control of the environment. The participant described this change as:

> *After a couple [breaths] I was like "no that's me, if I'm holding my breath I see down, every time I'm exhaling I'm down there, and every time I'm inhaling I'm up there" and then I tried to hold my breath both in the inhalation and exhalation and I was like* ***"Hey, yay, I got it"****.* (P17)

Regarding the audio cues, the majority of participants made a connection between the sound and the breath through the visual cues of their position in the environment:

> *When I'm staying level there [on the surface]... the sound gets a little bit violent I guess. It was just like, there was some sort of something like chords going on with some dissonance pattern maybe bit when I was level there I felt like there something transcendental creature got real angry about what I was doing and like the sound got violent and even although I enjoyed being level there for a while I felt "for this sound to change I have to move" and I went back to breathe in breathe out pattern again.*(P15)

Figure 5. Change in breathing pattern following realization of how the participant's breathing influences the system

Finally, some participants related the perceived motion cues to perceived bodily sensations of the breath. After the initial "a-ha" moment of breath awareness, the motion cues caused participants to be more aware of the range, rhythm, depth, and other subtleties of their breathing and the other bodily sensations that accompany inhalation and exhalation.

> *I paid attention to correlation and inhaling... feeling my body move, and also like the airflow through my nose, and my mouth... I feel like when my body became still I inhaled completely, and there is moment of no movement then that's when the motion stopped.* (P11)

Breathing patterns and perceived sense of agency

The comparison of breathing data of Session 1 (participants unaware of agency) and Session 2 (participants aware of the agency and interacting with the environment) revealed different breathing patterns and the qualities of the experience associated with the interaction. This is depicted in Figures 6 and 7. The upper images of both Figure 6 and Figure 7 reveal that when these two participants were not aware of their agency in the environment (were not aware of the changes their breathing was causing to the environment), the breathing patterns remained somewhat consistent within all three phases. However, the bottom images demonstrate that the changes in the phases are followed by the changes in the breathing patterns, indicating that the perceived agency in the environment in this case, influenced how the user interacted with the environment (leading them to take on more active role) and their experience of it.

> *The first one I feel like because I didn't know that I had any control over what was happening I think it was lot more chaotic in my mind. And the second one was lot more calming because I felt I had that control.* (P10)

An interesting finding is that the sense of agency in some participants defined the perceptive position of the participant. In the first trials, those who were not aware of the direct control they had of the system were more likely inclined to take a passive role in the environment similar to the "observer's perspective" or that the system was pushing them up and down.

> *In the first one I was thinking that something is pushing me up and down like bouncing... this time I was thinking*

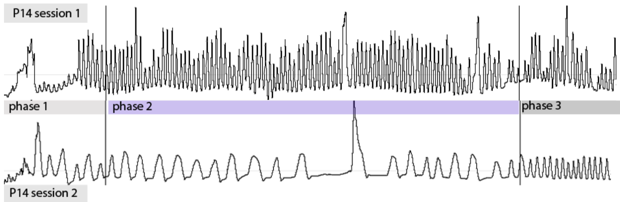

Figure 6. breathing data during Session 1: no perceived sense of agency vs breathing data in the Session 2: perceived agency (bottom image).

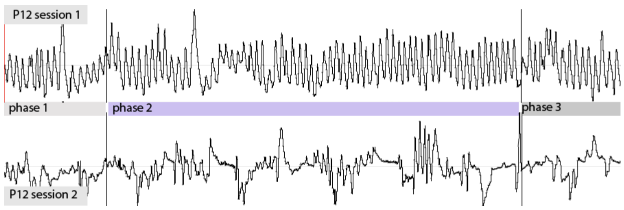

Figure 7. (upper image) breathing data in the Session 1 vs breathing data in the Session 2 (bottom image)

> *I am controlling this and I can calm this ocean... so I was feeling this was inside my body, it's not the system, it's inside of me.* (P12) (see Figure 7)

Creating the experience from "within"

Once the participants became aware of their breath, of the agency that their breath has in the environment and how they can control the experience, they started exploring the environment. After participants got familiar with the elements of the environment and identified the most pleasurable parts they started directing the experience from "within", through their breathing. Curating the experience through agency and perceived control over the environment helped the users to leverage the initial personal differences in initial reaction to the environment, while gradually familiarizing with the control they had in the environment.

Personal differences in experiencing ambiguous VE

Previous, real-life experiences influenced participants' experience of the environment; participants who fear water made negative associations with our environment and vice versa, participants who relate positive experiences to being in the water found the environment more pleasurable.

> *I didn't like the feeling of going underneath... probably not because of this experience but probably related to other experiences with water and because it looks a lot like water... [how does this make you feel] it's like a little bit of anxiety... or like fear in a way but not really fear because I know I can breathe.* (P10)

Following the evocation of previous experiences, the immersiveness of the medium triggered strong bodily sensations related to the overall quality of the experience.

> *I did experience that feeling of euphoria as I was coming up and and traveling upwards I did get that sensation of actually moving up and when I looked down I just really felt compelled this was overwhelming feeling for me to wanna go deeper... and I just wanted so hard to get rid of all of my breath so I could go deeper.* (P13)

> *It was kind of like swimming and holding a breath underneath the water... and then like I could feel that physical aspect to it.* (P7)

Perception of control alters the experience

A few participants initially experienced VE as anxiogenic or fear-inducing. However, they alleviated these initial negative associations once they realized that they were in control.

> *I was like "oh I'm in control actually" and that's very comfortable, because that anxiety went away straight away... it's very comfortable that anxiety was out of it... I can stay under the water as long as I want. That's totally fine – I told myself... and then I also see the patterns below and then I felt this urge to explore it.* (P15)

Curating the experience from a conscious control of a breath

In the second phase, once the participants were aware of their breath and control that they had over the environment, they would purposefully manipulate their breathing patterns to either stay in a preferred location in the environment or avoid potentially unpleasant stimuli.

> *I kind of found myself holding my breath when I breathe out because I liked the blue better the description of the VE... so I found myself kind of breathing out lot more than what I was inhaling that's what I was observing when I was really focused on my breathing.* (P16)

Some of the participants were able to identify moments when their breathing changed as a response to the environment, which induced a reaction. The reactions to irregular breath varied from focusing on breath closely to trying to change the position in the environment to a preferred one.

> *In that first phase I'd say I think I was just attuning to the environment. [how?] I listened to my breath and I realized because I'm not doing well, I suffer of sea sickness, so I was "I don't know if this is going work" and I realize that my breath was going faster than what would normally happen, but then I just tried to listen to my breath and that was pretty much what I did.* (P17)

Associating irregularity of breath with a particular part of the environment that helped participants know how to regulate breath when it becomes irregular:

> *Then I was asking myself: ok now I'm breathing quite heavily so... uhm... can I also maybe just try to get back to the white plane again?* (P8)

Subtle and unaware of influence of the environment on breathing patterns

In Session 1, only three participants were immediately aware of their agency. The data plots of the remaining eight participants indicate that there is an influence of the system on their breathing patterns. This influence is particularly clear in the moments of phase changes, revealing two trends:

1. Transient perturbation of breath by changes in the mapping
Figure 8 depicts the respiration sensor data for participant 16 in

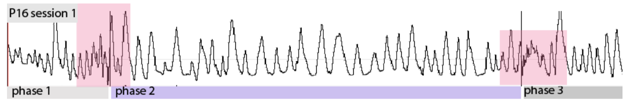

Figure 8. Respiration sensor data for participant 16 in the first session. Although P16 was not aware that their breath controlled the visual feedback, we observe shifts in breathing patterns following the changes between the three phases.

the first session. Although P16 was not aware that their breath controlled the feedback, we observe that transitions from phase 1 to phase 2 and from phase 2 to phase 3 were followed by changes in breathing patterns. Even though participants were not aware of the fact that they influenced the system, the data suggests that changes in the mapping of breath to the visual feedback induced perturbations of the participants' breathing patterns.

2. Sustained Influence of the mapping on the breathing patterns
Finally, the comparison of breathing patterns across phases showed that participants' breathing patterns changed on a longer time scale throughout the session. For example, the breathing period of P16 significantly changed between phase 1 and phase 2, as highlighted in Figure 8. In phase 2 participants tended to breathe at a slower rate, extending inhalation and exhalation over longer periods of time compared to phase 1.

DISCUSSION

In this section, we discuss the findings in the context of designing for breath awareness. This discussion is informed by participants' accounts about the process of becoming aware of their breath, and by our design decisions.

The role of sense of agency and control in overall experience

Understanding the control and engaging in the interaction impacts the quality of the experience and thus influences the experience-driven designs [12]. In our study protocol, we allowed participants to explore our system in Session 1 without giving away the details about how the system reacts to their breathing. Eight participants did not make an explicit connection between their breathing and changes in the environment in Session 1. We speculate that this happened due to an overall novelty with virtual reality applications, the lack of knowledge regarding the respiratory sensor, and that once immersed in the environment the participants were engaged in sense making of the scene rather than raising focus and awareness to the interaction. That could possibly explain why some of the participants reported that "something" [P12] was pushing them up and down, without realizing that that "something" was their breathing. Feeling of being dependent on the system while immersed in the VE caused unpleasant feelings that were alleviated once the participants became aware of their agency on the system. We find this to be a challenge to be addressed in future work. How we can design systems that make users aware of their agency in a subtle, less instructed way is yet to be addressed.

Interestingly, three participants did make an immediate connection between their breath and the environment. After the interview, when asked whether they meditate, and how often, those three participants reported that they regularly meditate. While we are careful not to draw strong conclusions from this observation, it has been shown that meditators have more accurate visual attention compared to non-meditators [19, 37] and this might explain why those three participants made an immediate connection.

In conclusion, while the system did not change, perceived sense of agency and control over the system determined the qualities of the experience: if the sense of agency was not perceived, the experience was more likely to be unpleasant. Understanding how the system could be controlled was crucial in a further unfolding of the experience. Participants exercised control especially in the parts of the environment that were more likely to induce fear and anxiety. At signs of discomfort caused either by the movement or audio-visual feedback, participants consciously changed their breathing to influence changes in the environment towards creating a more pleasant experience.

Complexity of the VE mediated through gradual introduction of the elements through phases

During the design process we were faced with the decision of how much feedback is optimal for eliciting breath awareness while preventing possible distractions. Through an iterative design process we decided to gradually increase the threshold for the stimulus, introducing sound as the first cue, and then movement as the second cue to breathing. This allowed participants to familiarize themselves with the environment before introducing more stimulating, and more obvious cues such as the movement along the vertical axis.

The majority of the participants described the up-down movement as the most dominating cue to one's breathing in our environment. One explanation might be that of the immersiveness of VR as a medium that can elicit bodily sensations related to locomotion. Moving on the vertical axis up and down was described as being on the roller coaster or a swing. In the second phase, the majority of participants' reports about breathing were related to the movement rather than sound. Sound as a cue was discussed within the first and third phase, when the movement cues were absent. The absence of the movement allowed the participants to listen and "attune" to their breath:

> *[in the end the third phase] I was just watching and I heard a sound but my attention and my focus was inside and just listening what was happening... in the second [the second phase] I was still doing that but because I knew I could control what I was watching instead of attuning to my breath I was using my breath to change what I was observing.* (P17)

Despite our attempts to understand an optimal amount of cues to guide the user's attention through the pilot study from which we drew insights for the final design presented here, some of the participants' accounts imply that a few things distracted them from fully attending to breathing. The main distractions are related to the interaction design: the velocity of the movement on the vertical axis was reported as too fast. Since the mapping of the movement was not elaborate in this iteration of the system, we see the potential of fine-tuning the mapping of the movement and better controlling for the velocity. We speculate that fine-tuning of the movement parameters will provide more opportunities for variety in how users interact with the system and how breath awareness can be raised in more subtle movements in the environment, and this will be explored in our future work.

Attuning to the environment

While we expected to see the changes in breathing patterns within different phases in Session 2 when the participants were aware of their agency and how they control the changes in the environment, unexpected findings emerged from Session 1. Even though the participants were not aware of the differences between the three phases, nor were they aware of how they influence changes in the environment, breathing data revealed that breathing patterns changed in participants (9 out of 11 participants) following shifts between phase 1 to phase 2 to phase 3. This suggests that our virtual environment influenced the breathing patterns through implicit mechanisms, and we are curious to explore this further.

Meditation tool

As a part of inquiry after the micro-phenomenology interview, we asked the participants: "If we tell you that this VE is a tool, what would you use this tool for?". The majority of the participants responded that they would use it to: overcome a fear of water, reflect, isolate themselves from distractions, or meditate. One of the participants even compared the breath-driven control to breathing exercises often done as an intro to mindfulness meditation practice:

> *it felt... it's kind of when you are meditating and you do breath work before. And so I felt kind of the same in terms I wasn't using breathing technique but to say "ok now I'm controlling my breath" and then with the white peaceful situation I attuned to my body and that was it, I wasn't controlling I let that go.* (P17)

Presence of visual cues helped the participants focus on their breath which is commonly reported as an obstacle in novice meditators:

> *You can pay more attention to the visual or what's in front of you in environment to make that difference in your body instead of having to pay attention to your breathing to a affect your breathing, you pay attention to the environment to affect your breathing.* (P10)

Traditional mindfulness meditation requires mediators to maintain some kind of *meta-awareness* so they can notice once their mind wanders off and they lose focus on their breathing and gently guide their attention back to their intended point of focus. This need to maintain a meta-awareness constitutes one of the main meditation challenges and obstacles especially for novice meditators. Similar to the playful interaction paradigm in the auditory environment of *Sonic Cradle* [73, 74], the audio-visual virtual environment in the current study was designed to subtly and unobtrusively help users to re-focus their attention to their breathing once they lost it – as if the system would simulate the meta-awareness that the users might not have developed yet. Instead of requiring users to maintain meta-awareness, our system was designed to help users re-orient their focus in a more playful manner, which we hope will eventually help them to more easily re-direct focus in their everyday life.

Commentary on the methodology: Can we trust the participant's descriptions?

In this study, the interviewer has been trained in the method, but none of our participants have been subject to a micro-phenomenology interview prior to participating in our study. While no method to our knowledge can provide us with conclusive evidence that participant's actual experience matches their description of it, we found some signs of such matchings. When we compared participants' interviews with their breathing data, it showed that the descriptions explained the breathing data such as changes in breathing rhythm patterns when participants reported that they changed their breathing, or holding the breath to stay in a particular part of the environment, or sudden deep inhales/exhales showed in plots. Despite the difficulties that some of the participants experienced with an evocation of the experience, we are confident in the validity of the descriptions because their descriptions can explain the breathing data and the breathing data corroborates their descriptions. However, we are yet to explore what is the level of detail in the descriptions that we can obtain from participants and how fine-grained descriptions correlate with the breathing data.

CONCLUSION

Our motivation was to gain a deeper understanding of how the experience of becoming aware of breath in VE unfolds. Previous mindfulness-based designs that employ breath demonstrated the important role that breathing and breath awareness hold in mindfulness practices. However, the understanding of the process of how people become aware of breath through embodied interaction was largely missing and the goal of this study was to take us a step closer to that knowledge. Our contribution is threefold: First, we presented the design of a system that employs breathing as embodied interaction in VE for eliciting breath awareness; Second, we conducted a micro-phenomenology inquiry and unveiled the mechanisms of becoming aware of breath; Third, we presented the findings that revealed the process of becoming aware of breathing in VE and demonstrated the importance of a sense of agency, understanding of control and possible subtle impact of the environment on breathing patterns without users being aware of it. In addition, some of the initial unpleasant experiences and personal differences in the quality of how participants experienced VE can be alleviated if users are enabled to curate their experiences. Finally, we contribute to the research on micro-phenomenology and HCI by revealing that participants' descriptions of their experience can describe their breathing data. This indicates the potential of micro-phenomenology and motivates us to continue to explore this methodology paired with physiological data in future work.

ACKNOWLEDGMENTS

The authors would like to thank all the volunteers for participating in the study, Ash Tanasiychuk for tireless proofreading, and the reviewers for their valuable feedback.We would like to acknowledge that this research would not be otherwise possible without the grant support from The Social Sciences and Humanities Research Council of Canada (SSHRC), and equipment support from Natural Sciences and Engineering Research Council (NSERC).

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