Inner Garden: Connecting Inner States to a Mixed Reality Sandbox for Mindfulness

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Figure 1. Inner Garden: A sandbox (up left) is connected to physiological sensors (bottom left) to create a mindful interactive experience where the user can shape her own world that evolves according to her breathing and heart rate (center). The user can then decide to be immersed inside this world thanks to a Head Mounted Display (right) for a moment of solitude and meditation.

ABSTRACT
Digital technology has been completely integrated into our daily lives, yet the potential of technology to improve its users' life satisfaction is still largely untapped. Mindfulness, the act of paying a deliberate and non-judgmental attention to the present moment, has been shown to have a positive impact on a person's health and subjective well-being – commonly called "happiness". Based on an iterative process with meditation teachers and practitioners, we designed a new tool to support mindfulness practices. This tool takes the shape of an augmented sandbox, designed to inspire the user's self-motivation and curiosity. By shaping the sand, the user creates a living miniature world that is projected back onto the sand. The natural elements of the garden are connected to real-time physiological measurements, such as breathing, helping the user to stay focused on the body. Moreover, using a Virtual Reality headset, they can travel *inside* their garden for a dedicated meditation session. Preliminary results seem to indicate that the system is well suited for mindfulness and induces a calm and mindful state on the user. The meditation teachers envisioned the use of Inner Garden in their practice.

Author Keywords
Mixed Reality; Tangible Interaction; Spatial Augmented Reality; Virtual Reality; Calm Technologies; Mindfulness

ACM Classification Keywords
H.5.1 Multimedia Information Systems: Artificial, augmented, and virtual realities

INTRODUCTION
The pervasiveness of computational devices found nowadays is getting closer to what was envisioned by Weiser when describing Ubiquitous Computing [54]: we constantly carry with us one or more computers that are always on, and on which we increasingly rely to handle different aspects of our lives. However, there is no evidence that this proliferation of digital technologies in the last 20 years made us any happier [19]. At the cornerstone of Weiser's vision was the sense of *calm* [55] – where technological devices do not compete for the user's attention, but are instead available when required –, putting humane experiences before the efficiency and connectivity. This has not yet seen a widespread adoption in information technologies.

Recently, human-computer interaction (HCI) researchers, designers and technologists started looking at computers not merely as devices to interact with, but as a support of positive changes in their users' lives, aiming to foster subjective well-being, more commonly called "happiness". Examples of this can be seen in the combination of positive psychology [44] – the scientific study of optimal human functioning and flourishing – along with the fields of design [9] and HCI [5, 40]. Subjective well-being is a multifaceted concept often described as a combination of *hedonism* – maximizing pleasure – and *eudaimonia* – developing our human potential [42]. There is a multitude of factors that have been shown to contribute to happiness and could benefit from technology [5], e.g. positive emotions, motivation and engagement, self-awareness, and mindfulness. Among these, this work focuses on *mindfulness* practices.

Mindfulness can be considered as the opposite of mind wandering, which has been demonstrated to cause unhappiness [27]. Kabat-Zinn defines it 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*" [24]. While mainly used in Buddhist traditions, it has been adapted and brought to a more western audience a few decades ago. It has been empirically tested and proved to be a good tool to train attention [3], for health care, mental illness and education [56]. More specifically, it has been integrated in an eight-week program course – Mindfulness-Based Stress Reduction (MBSR) [23] – to help people cope with stress, pain and depression [15]. More recently, the Mindfulness-Based Cognitive Therapy (MBCT) program has been proposed and has proven effective in treating depression, preventing relapse and promoting well-being [43].

While the mental and physical health benefits of mindfulness have been demonstrated, mindful practices are not easy to integrate into a daily routine. One of the most common said practices is mindfulness meditation. Similar to physical exercises, attention training requires practice and efforts, however, unlike physical activity – for which we can design playful, competitive or compelling settings that contributes to motivate its practice (e.g. sports) [16] –, meditation is a tricky activity to make engaging. Trying to contemplate without judgment or specific goals feels idle, like actively *doing nothing*. For novices, mindfulness meditation can be deceptively hard to practice for more than a few minutes without being distracted, yet involving any external source of motivation would be contradictory with mindfulness itself. The challenge we tackle in this paper is how to design artifacts that are both intrinsically engaging and foster mindfulness practices.

We present Inner Garden, a multi-modal tangible artifact that takes the form of an augmented sandbox depicting a small world (Figure 1), designed to implicitly support mindfulness exercises. The garden combines Physiological Computing [10] with Spatial Augmented Reality [38], Tangible Interaction [20] and immersive Virtual experiences. The Inner Garden's metaphor is anchored in reality using physiological activity and real sand. It is designed both as an ambient display for self-monitoring and as a support for more involved mindfulness exercises: breath and body awareness. The user can shape the terrain with his or her hands or tools, and affect its evolution with his or her internal state. By contemplating and interacting with the garden, the user receives biofeedback (e.g. the breathing controls the waves, changing the sea level and its sound accordingly). This gives a gentle-yet-constant reminder of his or her own bodily activity, providing an anchor to the present moment (Figure 3). Using a head-mounted display, the user can travel *inside* his or her own garden, for a moment of solitude and meditation, still accompanied by the biofeedback.

The three main contributions of this work are: 1) a prototype leveraging Spatial Augmented Reality, Tangible Interaction, Virtual Reality and Physiological Computing for the purpose of supporting mindfulness practices (namely, breath and body awareness), 2) design considerations and takeaways from iterations with experts, and 3) interviews with meditation practitioners that tested the system.

RELATED WORK

The work presented in this paper is at the intersection of different fields: it builds on top of technologies for mindfulness and is implemented using Physiological Computing, Virtual Reality, Spatial Augmented Reality and Tangible Interfaces. A brief introduction to these fields is presented below.

Technologies for Mindfulness

Most technologies that support mindfulness activities rely on guided sessions [18, 46] or leverage social networking features [33], most often delivered through the web or mobile applications. Recently, Virtual Reality (VR) has been used to deliver more immersive experiences, using either guided sessions [6], brain computer interfaces [1] or both [28]; other VR applications provide procedural landscapes based on the user inner activity [49, 7]. Further along the spectrum of reality-virtuality, we find the work of Vidyarthi et al. [52], who proposed Sonic Cradle, where users sit on a hammock in a sound-proof room where their breathing patterns were amplified through sounds. This installation focuses on the embodiment of inner activity to anchor the user into reality, yet it requires a dedicated room, thus it is not part of the user's daily environment.

It is possible to divide the previous technologies into 3 groups: 1) always-available mobile applications, 2) immersive VR sessions, 3) and dedicated rooms with embodied installations. With Inner Garden we propose a middle ground between these options, with a locally-available ambient display which provides an embodied experience, with optional immersive sessions.

Measuring and Displaying Bodily Signals

Mindfulness meditation is based on paying attention to the real world (i.e., what is currently happening, either externally or internally), and it frequently uses the practitioner's inner activity as an anchor (e.g., breath awareness). Nowadays it is possible to monitor in real time some aspects of our physiology. The Quantified Self (QS) [58] is an increasingly popular movement that consists in keeping a log of different metrics related to health or physical activity, which can be used to gain insights about one's own body. Lately, extensions of the QS to cognitive tasks has also been proposed [30]. Different works relate to the tangible and social representations of this data, for example creating a 3D printed object based on a running session [26]. However, the quantification of this data enables comparison – with oneself and others –, which directly leads to striving (and this should be avoided with mindfulness). Bodily signals have been used in the context of calm technologies, for example SWARM [57] is a wearable with sensing capabilities to mediate affect. Similar in spirit with our system is BreathTray [34], an ambient desktop widget that help users to control their breathing patterns. Sonne and Jensen [47] created a game for children suffering from ADHD (Attention Deficit Hyperactivity Disorder) based on slow breathing patterns. Gervais et al. [12] created a toolkit to create tangible animated representations of real-time physiological data. In addition, they used it to create a tangible avatar for a breathing exercise to promote relaxation. However, these systems were not specifically designed for mindfulness.

Spatial Augmented Reality and Tangible Interfaces

Spatial Augmented Reality (SAR) [38] consists in displaying spatially coherent digital information in the environment, either using projectors or screens. Closely related with SAR are Tangible User Interfaces (TUI) [50], which provide physical representation to digital information. In combination, these technologies enable the user to see and interact with digital information using materialized metaphors. SAR has already been used in conjunction with deformable materials. Illuminating Clay [37] has been the first system to combine the two elements. It uses clay to represent a landscape which can be directly shaped with the hands. The result of landscape analysis functions is displayed directly on the clay. In the artistic project *EfectoMariposa* [13], the projected simulated world is alive and evolves on its own – e.g. elements in the mini-world evolve without any user intervention. Dynamic augmented worlds can also be navigated virtually: in MadSand multiplayer game [41], one of the players creates the mini-world using an augmented sandbox and the second one can navigate it in real time using a desktop computer.

Interfaces involving SAR and TUI make abstract topics easier to grasp by enabling the user to experiment hands on [45, 35]. In our case, we present the user their own inner state, giving life to a small world, an embodied meditation metaphor.

INNER GARDEN

Our system is inspired by both the reflective and metaphoric nature of zen gardens as well as the playful and experimental nature of sandboxes. Zen gardens are all about careful placement of elements and are often used for contemplative and meditative purposes. On the other hand, sandboxes call for interaction and experimentation. We purposely used a gardening metaphor to encourage the *continuous practice* of mindfulness; Inner Garden grows with time and with each meditation session a user does. Indeed, mindfulness is not about the quantification of the current experience (e.g. how you performed when watering your garden today), but is instead about the ongoing process of being able to identify a wandering mind and returning it to the present moment (e.g. watering your plants every day). The gardening metaphor puts the user in charge of a living artifact, and it provides a source of relatedness [8].

The garden's sandbox contains polymeric sand (sand with an added polymer that keeps the "wet sand texture"), which can be reshaped at any time using bare hands or tools and determines the topology of the terrain. The real-time simulation handles the generation and evolution of the living mini-world, which is then rendered on the sand using projection. The lowest areas are filled with virtual water, which level is mapped to a breathing sensor attached to the user. Breathing patterns therefore generate waves, producing subtle sound effects audible even when the user is not directing his or her attention on the garden. The user can simply contemplate the mini-world, the sea moving with his or her breathing and the clouds slowly passing by. Finally, the user can decide to go *inside* the mini-world for a moment of solitude [11], selecting a location by placing a mini-avatar in the sandbox (Figure 2), and then using a VR helmet. During the immersive session, the user will find him- or herself sitting at the corresponding location in the garden, facing a campfire that intensifies slightly when the user is breathing out (Figure 1 right). At all times, biofeedback is part of the nature itself, as a gentle reminder to focus on his or her internal state.

The Garden's World

The living mini-world is composed of different elements, each one evolving at a different pace. It consists of the terrain, the sea, life in the mini-world, weather conditions and time. These layers are depicted in Figure 3.

Terrain The sand defines the topology of the mini-world. According to the elevation and slope, sections of terrain with specific properties are defined. For example, if the slope is too steep, no plants will grow; if the terrain is too high, snow will accumulate.

Sea The sea level divides what is above and what is underwater. This level is a fixed value that is set according to the height of the sandbox. Sections of terrain that surround the sea level will not contain flora, having a beach instead.

Life Two types of life form exists in the mini-world: flora and fauna. The flora consists of grass and trees that grow over time. The fauna, while not explicitly made visible in the mini-world, manifests its presence with sounds (birds or crickets).

Weather The weather elements that are simulated in the mini-world include wind and clouds. The wind is one of the central aspects as it is directly linked to breathing. It also impacts other elements of the mini-world. Namely, clouds move according to the wind's speed. In VR, it also directly affects the movement of the trees and the intensity of the campfire.

Time The mini-world has its own internal clock and the passing of time can be made constant (e.g. following the local time) or variable. The clock defines the amount of light and the sun position, which in turn affects how the clouds shadows appear. The day/night cycle also influences the active fauna (birds during the day, crickets during the night).

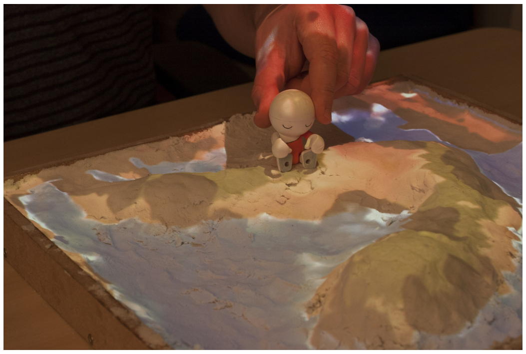

Figure 2. A physical avatar allows the user to choose the location where he or she wants to be immersed in his or her mini-world.

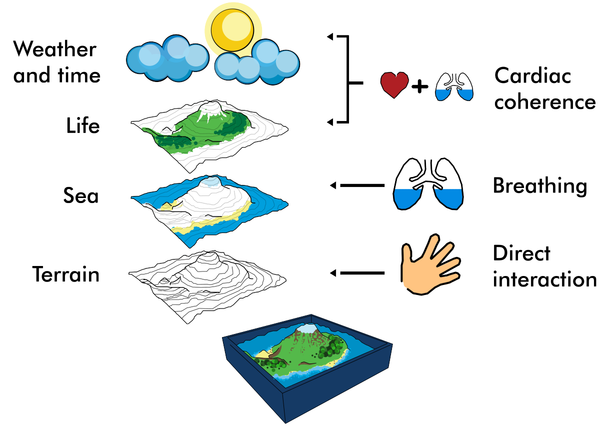

Figure 3. The layers of the Inner Garden and their connection with the user. From bottom to top: the sand is manipulated by hand; the level of the sea is controlled by breathing; vegetation growth and weather depend on cardiac coherence.

Physiological Signals

Inner Garden evolves and reacts to the user's real-time physiological measurements. It acts as both an instant biofeedback device as well as a long term and motivating ambient support. The measured physiological activities and their mapping to the dynamic elements of the mini-world open a wide number of design possibilities. We present the ones we selected and the rationale behind them (Figure 3):

Breathing The oscillating breathing patterns are mapped to the water level (which creates waves), and to the wind strength (creating gusts of wind). These elements are naturally periodic in the real-world, creating a coherent experience. All the experts we interviewed found the water biofeedback interesting since they use similar metaphors in their meditation sessions.

Cardiac coherence (CC) This metric is the positive correlation between the fluctuation of the heart-rate and the breathing cycles, when taking regular, slow and deep breaths. The resulting state has positive impact on well-being [31] and it is associated with a relaxed state. CC is a metric that varies slowly over time, therefore we used it as a subtle indicator of the overall "healthiness" of the garden. When in good health, the amount of clouds reduces, flora's growth speed is increased and sounds caused by the fauna are more present. Note that there is no obvious "unhealthy" state; fauna might hide, but trees will not start dying as a result of a low CC score. This is to avoid the introduction of judgmental effect. CC might be correlated with a relaxed state, but this is not a requirement for practicing mindfulness.

We also considered and discarded two additional sources of feedback:

Heartbeats We avoided direct feedback of the heart beats, since the user cannot control them directly. Moreover, because the rhythm is naturally fast, we considered it could lead to unnecessary discomfort. One of the interviewed experts pointed out that since mindfulness is about acceptance, observing a state like stress should not trigger "negative" biofeedback loops, yet their design should be considered carefully, specially for novice users. We envision the possibility of using heart beats to controls different rhythmic components of the mini-world, such as ambient music.

Electroencephalography (EEG) EEG measures brain activity, and it can detect high level mental states, such as emotional valence and arousal (i.e. if the user is experiencing positive or negative emotions, and how intense they are) [59] or the level of attention. Previous versions of Inner Garden included EEG, but it was excluded from the current version given both the inaccuracy of current methods and the difficulties to equip and calibrate them outside of the lab. In a foreseeable future the detection of high level mental states will be more robust, and EEG electrodes could be embedded in the Head Mounted Displays, enabling its use during immersive sessions, as done in [28].

Designing for Mindfulness

While designing Inner Garden system, we came across different problems and considerations about supporting mindful practices and experiences. As part of the design iterations we tested the system with five experts, either in meditation or medical practitioners initiated in meditation practices. Their diverse backgrounds allowed us to gather feedback from different point of views. Each expert's background is detailed in Table 1.

EXPERT ID	BACKGROUND
E1_Teacher	Transcendental and mindfulness meditation teacher
E2_Psychomotor	Psychologist and psychomotor therapist
E3_MBSR	Head of MBSR center
E4_Psychologist	Psychologist interested in cardiac coherence
E5_Buddhist	Lama of a Buddhist center (Buddhist monk)

Table 1. The experts interviewed along with their backgrounds

Each of the experts was invited for a private session. We described the system and then equipped them with the breathing sensor. After an incremental demonstration of the available features, they were left free to experiment, usually making spontaneous comments in the process. After that, we performed an unstructured interview to know more about their experience and their opinion about the system as a tool for mindfulness. After each session the system was updated taking into account the obtained comments. The resulting design considerations build on the work of Calvo and Peters [5], and are presented below.

Distraction vs Guidance

There are two main approaches to support mindfulness, either provide direct guidance (e.g. external stimuli that point towards the breathing) or to train the required abilities (e.g. requiring focus on the breathing even in the presence of distractions). We chose to include both in a very subtle manner. The sea and wind present aural and visual feedback as a constant reminder of the breathing while animal sounds provide distraction from it. Moreover, since CC is based on consistent and slow breathing cycles, the stop in animal sounds provides a feedback that the breathing frequency is becoming inconsistent.

The pace at which the simulation runs and at which change happens needs to be carefully considered. Like guided meditations, some moments where nothing is happening or heard is required for people to focus, before offering a reminder to come back to the breath. E2_Psychomotor found some of the sounds a little too erratic and distracting while E1_Teacher and E3_MBSR considered these as interesting elements that could provide exercise to train attention. This tends to show that the pace at which events happens should be slow and progressive.

One of the main considerations of E1_Teacher for using Inner Garden in his teaching was how to frame an exercise without any external control. He suggested using the day/night circles to define the length of the exercises, while preventing ending the exercises abruptly (e.g. at nightfall). One interesting aspect for him was the use of naturally occurring events as a timer enabling the user to simply continue with the exercise if desired.

Keeping it Minimalist

A minimalist design can create an environment that has very few distractions, enabling the user to focus. Carefully chosen ambient biofeedback that is thematically built into the system – i.e. nature elements moving on a deserted island – provides a unified minimalist experience. E1_Teacher found the setup visually appealing but sometime hard to focus on. The constantly changing terrain was too detailed and dynamic for him. He suggested more minimalistic textures and slower movements. To address this issue, we reduced the overall speed of the clouds, the range of the sea waves, and the contrast of the textures.

Non-judgment and Non-striving

One of the core aspect of mindfulness is trying to be non-judgmental of your thoughts and adopting a non-striving attitude. We found these aspects were the trickiest part to design for, as one of the main motivation for creating a system supporting mindfulness is in making the activity more attractive and engaging. Usually, to increase engagement, goal-setting is efficient. However, as previously mentioned, it is relatively incompatible with a non-striving attitude. This is why we based its design on exploratory open-ended toys.

One way to get around goal setting is to provide a sense of progression related to the *practice* of the activity and avoid any explicit evaluation of how well a session went. This is also why we consciously avoided any *quantified* data and instead provided *qualified* feedback that is also fleeting – i.e. there is no record of your past breathing patterns or how your cardiac coherence evolved throughout the session. Moreover, to make the practice of mindfulness motivating every day, we added a localized biomass intensifying mechanism. Every time the user chooses to meditate at a specific area in the garden, it acts as a "watering system" for the biomass located there. That is, grass will grow greener and the trees taller, leveraging once again the gardening metaphor. It is based on the completion of an exercise (a given amount of time), and it avoids any negative progression: E1_Teacher insisted that the garden should not dry out if the user misses a day or two of practice – it should simply stay in the same state. This is also backed by the literature, that indicates that positive-only feedback (or progression in our case) is better for novices [17], and would satisfy the eudaimonic personal-growth aspiration [42].

Promoting Acceptance

Exercising acceptance – accepting what is happening, in contrast with the desire or ability to change it – is a key aspect of mindfulness. To train acceptance, the user must acknowledge that the garden will never be complete, and every time he or she modifies the terrain, the life will reset. The user must accept that there are consequences of his or her actions that are out of his or her control. Another way acceptance is exercised is with the immersive session. The user selects where to do the session with a tangible avatar before starting. Then, they can contemplate the surroundings, but cannot navigate the virtual space.

The biofeedback is itself not filtered allowing the user to face his or her own internal states, e.g. if a user starts breathing inconsistently, the water will reproduce this behavior. E3_MBSR considered that the user should exercise the ability to observe negative states (such as stress) without triggering a negative feedback loop, which is related with eudaimonic's self-acceptance aspiration. Even when this seems opposite to what E1_Teacher recommended in the previous section (no negative progression), they are complementary aspects: the user is exposed to both positive and negative states, but only the positive states (daily practice) have a lasting impact on the system.

Promoting Autonomy

This aspect is a core component in both intrinsic motivation and eudaimonic development. It is important to allow the user to control the boundaries of the experience along with when and how the feedback occurs. Ambient information is well suited for this, since it does not impose on the user. Therefore, the user has control over how fine grained he or she needs the information retrieval to be. A more directed attention enables more precise information to be derived while a soft focus will let unconscious mental processes do the monitoring. Moreover, sound is a modality that is easy to either tone down or disable by the way of volume control, if the feedback turns out to be too invasive. When we asked the experts about offering the possibility of controlling the moment of the day in the garden to suit individual preferences in meditation settings, they kept referring to such possibilities as “very ludic”, but were concerned that too much control and options will prevent the user from exercising *acceptance*. E1_Teacher and E3_MBSR said that such customization could be useful to define a starting point for the meditation session.

Using Tangible Interaction

A lot of attention-directing exercises leverage the body and its sensation to stay in the present moment (e.g. yoga, guided meditation, tai chi). E5_Buddhist was concerned about the increasingly prevalent disconnection from the body in favor of the world of the mind and thoughts. This expert especially liked the use of the sand in Inner Garden as a tangible, direct and visceral way to reconnect to physical sensations, potentially “bypassing” the mental. E2_Psychomotor and E4_Psychologist found the SAR installation could be particularly useful in physiotherapy, in order to let the patient “get back” to their body. While trying the system, all experts enjoyed doing back and forths between performing modifications on the landscape and periods of contemplation.

Choosing the Right Reality

The use of Virtual Reality (VR) or See-Through Augmented Reality (ST-AR) helmets, such as Oculus Rift [36] and Microsoft Hololens [32] respectively, can provide immersive experiences that can be leveraged in interesting ways for mindfulness purposes, and were used in the past [6, 1, 28] for this objective. For example, these technologies can prove useful when looking for moment of solitude [11], by blocking or tuning out external stimuli. However, completely traveling to an alternate reality seems to go against the “acceptance” of reality described earlier. On this matter, E4_Psychologist also raised concerns on using a VR experience in cases where user has psychological troubles to differentiate what is real and what is not, such as persons suffering from schizophrenia. For these reasons, we made sure that the system was designed around a SAR experience. SAR is interesting because it directly uses the physical world as support and provides a shared experience that does not require users to wear any equipment, unlike ST-AR systems. From this experience anchored in reality, we added a VR modality that allows users to travel to a spot inside their garden. Because of this AR-VR transition, the VR experience is anchored on a real-world element: before the visit, the user built the virtual world with his or her own hands, and placed an avatar on the location they want to travel to. Moreover, even if the virtual world is completely computer generated, the biofeedback is always present, keeping the user aware of his or her own body. For those cases where VR is not recommended, such as with young children, SAR is a very interesting alternative to explore.

During the iterations we experimented with an intermediate Augmented Virtuality modality, where it is possible to see and touch the sand while wearing the VR helmet. This was accomplished by rendering the scene from the user’s head position, and using a Leap Motion (attached to the front of the helmet) to provide feedback about the hands position (Figure 4). The resulting hybrid modality mixes both the immersive experience with the tactile feedback from the sand. Experts were concerned that this feature will render the system “too ludic” for mindfulness (i.e., too much playfulness can disperse the user’s attention, which is the opposite of the system’s objective). This concern might be due to the high degree of interactivity with the virtual elements, that drives away attention from the physically based elements. This modality, while promising, requires further consideration.

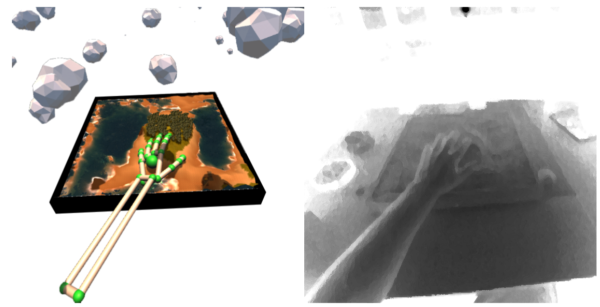

Figure 4. Mixing the SAR and VR experience. Hands are captured by the leap motion. This allows modifying virtual elements (e.g. clouds). A precise mapping between real and virtual allows one to modify physically the sandbox, while being immersed in VR.

Design Overview

The starting point of Inner Garden took inspiration from zen gardens, and it was built on top of existing mindfulness applications, leveraging tangible artifacts. The exchanges with experts either validated or complemented the design considerations we found in the literature, and enabled us through an iterative process to create an engaging artifact for mindfulness. We consider the lessons learned in the process can be of use not just for the reproduction of the system (detailed in the next section), but also when facing the design of novel positive computing artifacts.

SYSTEM IMPLEMENTATION

The final version of the system is composed of five modules: projector-camera calibration, surface scanning, physiological controller, simulation and rendering (Figure 5). The components were implemented using 3 frameworks: vvvv [53], Unity3D v5 [51] and OpenViBE [39]. The whole installation runs on two computers: the graphical pipeline and simulations runs at 80 fps on a Intel i7 Windows 10 desktop computer equipped with a NVidia GTX980Ti graphic card, while the physiological controller runs on a dedicated laptop computer running Kubuntu 14.04 in order to reduce signal acquisition latency.

Projector-Camera Calibration

The SAR setup is comprised of an ASUS short-throw projector to augment the sand and a Microsoft Kinect v1 (Figure 6) to capture the sand’s topology. The projector’s intrinsic (lens properties) and extrinsics (position and orientation) were calibrated using OpenCV [21] camera calibration tools (2D to 3D calibration), while the Kinect extrinsics were calibrated using the Kabsch algorithm (3D to 3D alignment: rotation

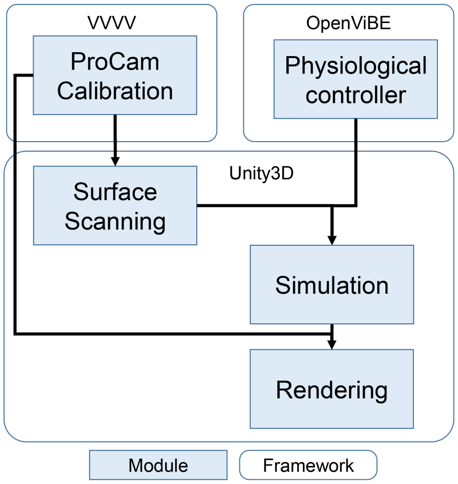

Figure 5. Inner Garden modules. The projector camera-calibration is performed offline, and the physiological controller runs on a dedicated computer. The main application performs the surface scanning, simulation and rendering, and it was implemented using Unity3D.

and translation). The sandbox was used as the common frame of reference. The calibration is performed offline. We used a 40×40×4cm sandbox. Different shapes could be studied, notably in the case of multiple users where circular shapes could ease collaboration.

Surface Scanning

The acquisition of the Kinect information (Figure 7) is performed on a worker thread on the CPU, while the computation of topological information is performed on the GPU. First, the Kinect's depth information is converted into a point-cloud (sparse world positions) using the depth camera's field of view. Then, the Kinect's extrinsic calibration is applied, to obtain the point-cloud in the sandbox referential. Being in the same coordinate system, it is possible to identify the points that are inside of the box, or on areas of interest around it. Then, topological information can be computed: for every point of interest, it is possible to know the height from the base, and the associated normal along with the time from its last modification. Because the Kinect's depth information is noisy, changes under a threshold of 2 cm are ignored.

The detection of the tangible avatar is done using the height information. The avatar can be detected in one of two locations: 1) on a predefined area near the sandbox, or 2) on the surface of the terrain. In the first case, the terrain is updated continuously. The moment the avatar is removed from the preselected position, the update of the terrain geometry is paused. From this point on, significant changes on the heightmap are assumed to belong to the avatar

Physiological Controller

The physiological controller uses the TOBE framework [12], including both the sensors and the signal processing software. In terms of sensors, we used a Mio Fuse smartwatch for measuring heart beats and a homemade belt based on a stretch sensor to measure breathing. The latter is comprised of a

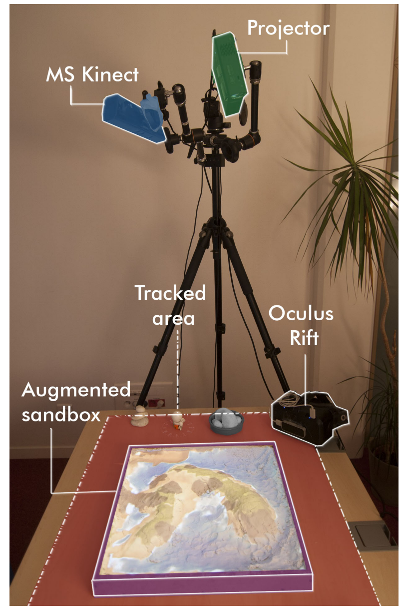

Figure 6. Installation setup: Projector (green), Kinect (blue) tracking the augmented sandbox (purple) and tokens over the table (red zone). The VR headset equipped with a leap motion stands at the back of the table.

conductive rubber band that was mounted as a voltage divider and connected to an instrumentation amplifier. It was then connected to a custom printed circuit board (PCB) that is directly embedded into the breathing belt. The PCB has a Bluetooth 4 module to stream the data to a laptop computer to be processed using OpenViBE, where the value is normalized using a moving window. Finally, the normalized information is sent to Unity3D using the LSL protocol, a network protocol dedicated to the streaming of physiological data[1].

[1] https://github.com/sccn/labstreaminglayer

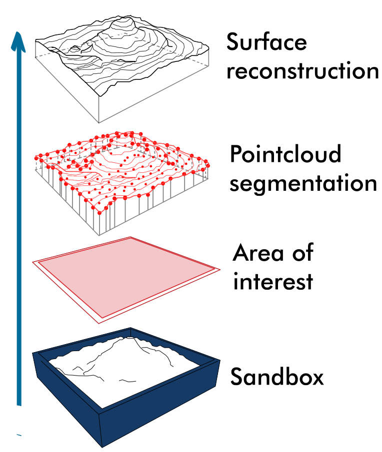

Figure 7. From the bottom up, how the tracking information is performed. Starting from a predefined region of interest, the Kinect point-cloud is segmented, then the per-point height and normal are computed.

Simulation

The simulation handles all the different elements of the garden's world (Figure 3). The generation of the mini-world's topology is created using the result of the surface scanning step. The topological information is used to classify the terrain in different region types (e.g. under water, above water, with snow, too steep to grow life). For each point of the sandbox, the growth of different kinds of vegetation is controlled by the time since its height changed, along with the region type. Therefore, each point will be assigned a color that will result in the terrain texture. Then, assets such as trees are instantiated based on the terrain texture. Finally, virtual elements are added, such as clouds, sun position and stars. These virtual elements are visible while in VR, and they influence the illumination in SAR.

Rendering

Finally, the scene is rendered from the appropriate virtual camera, depending on the output modality (SAR or VR). In the case of SAR, we create a virtual camera using the projector intrinsic and extrinsic parameters obtained previously. The rendering is then display using the projector. In the case of VR, the virtual camera is positioned at the avatar location inside the sandbox, and then visualized using an Oculus Rift DK2.

INTERVIEWS WITH PRACTITIONERS

To complement the feedback from experts, we conducted interviews with meditation practitioners to collect feedback from potential end users. Participants were recruited through the newsletter of a non-profit association that gathers people interested in meditation. 12 females took part in the study, mean age 45 (SD: 11). Most of them (7) practiced meditation regularly – several times a week or every day – but only 3 explicitly mentioned mindfulness practices, in contrast with other meditation practices. The study comprised of 5 stages (Figure 8).

Protocol

The participants entered a dimly lit room and filled out a consent form. Afterwards we introduced the features of the system progressively: shaping the sand, dynamic world, breathing (they were equipped at this moment), and finally the head mounted display. As we explained the breathing, the users could see their breathing projected onto the sand, they were also encouraged to touch it and play for a few moments, in order to see the connection.

After the system introduction, the participants filled several questionnaires so we could know more about their profile. The period during which they filled these questionnaires was used as the breathing baseline. The questionnaires were:

1. A demographic questionnaire
2. The five facet mindfulness questionnaire (FFMQ) [2]: a questionnaire evaluating how "mindful" they are during their everyday life
3. The state-trait anxiety inventory (STAI-YA) [48]: and a questionnaire assessing their present anxiety

Then we instructed the participants about the principles of mindfulness. On par with the instructors we met, we told participants that newcomers to mindfulness meditation could focus their attention on their breathing, taking deep and slow breath. Then the first meditation session occurred, using one of the SAR or VR modality to interact with the system. In the VR condition participants would pick their location using the token (Figure 2); in the SAR condition participants could freely manipulate the sand while meditating.

After 10 minutes – the length suggested by E1_Teacher – we interrupted the meditation exercise and participants filled the Toronto Mindfulness Scale (TMS), a questionnaire assessing how one was mindful during a specific exercise [29]. They had the opportunity to rest for a little while before we prompted them with a second meditation session, using the other interaction modality. Again, after 10 minutes they were interrupted and answered the TMS.

Before the exit questionnaires, participants were invited to use freely the system, without any guidance: they could shape sand, use VR or focus on breathing as they wished. When they finished to do so – usually after 5 min –, they filled three questionnaires:

1. The STAI-YA questionnaire, the same as the beginning of the study
2. The system usability scale (SUS) [4], which, as its name indicates, helps to evaluate the general usability of systems and services
3. Custom questions regarding the acceptability of specific aspects of the system

Finally, we conducted an informal interview with the participants, freely exchanging about the system for 20 to 30 minutes depending on the person.

Questionnaires Results

Concerning the profile of the participants, the FFMQ questionnaire corroborated the meditation practices declared by the participants at the beginning of the study. Regular practitioners scored above the average of our population – on a scale ranging from 39 to 195, the mean of the 5 traits measured by the questionnaire was 146.2 (SD: 14.75). A Wilcoxon Signed-rank test yielded no significant difference ($p = 0.13$) between the two interaction modalities concerning the TMS questionnaire – overall mean: 34.91 (SD: 7.37), scale ranging from 0 to 48. This result may imply that the system induces a mindful state, regardless of the chosen modality. As for the STAI-YA questionnaire given before and after the exposition to the system, the same statistical test showed a significant difference; participants were less anxious at the end of the study (mean: 25, SD: 5.23) as compared to the beginning (mean: 31.50, SD: 10.71), $p < 0.01$ – scores between 20 and 80. Even though mindfulness meditation is not about reducing stress per se, our system may induce calmness. This is reflected by the breathing rate of the participants, that were significantly lower during both mediation sessions, as compared to a baseline recorded at the beginning of the session (9 breaths per minute vs 17). The average SUS score was 80.82

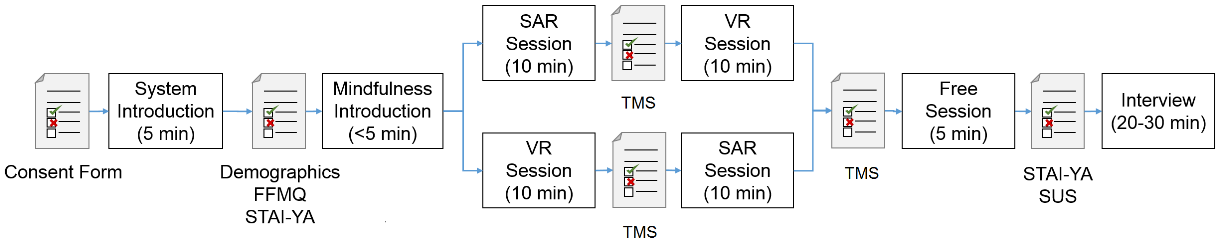

Figure 8. The 5 stages of the study and the questionnaires used. The stages involved: description of the system, two consecutive meditation sessions – SAR and VR, the order of the conditions counterbalanced between participants – , a free session, and finally an informal interview. Various questionnaires, measuring mindfulness and qualities of the system, were given during the study. Overall, a session lasted 1.5 hour.

(SD: 11.78) – scale between 0 and 100. Overall, this indicates that the system has good usability in both its SAR and VR modalities.

Feedback Discussion

The feedback we received was converging around recurring themes: the SAR and VR modalities and the multisensory experience.

VR and SAR

The participants were divided between which modality (SAR or VR) they liked the most – this was not caused for an order effect, since only 7 out of 12 participants preferred the first modality they tried. About half the participants mentioned VR as the best part of the experience, praising the immersion and the sense of control over the environment. Some participants, used to meditate with their eyes closed to fully concentrate, highlighted that the VR world enabled them not to be disturbed by external distractions while having something to look at. The other half of the participants (5/12) mentioned problems related with the heaviness of the VR headset and found the graphics too simplistic. One of the recurring comments was about the limitation of not being able to move in VR and explore the mini-world. This design choice was intentional, in order to prevent both simulator sickness and to foster acceptance, as discussed previously. However, it would be interesting to explore the potential benefits of virtual meditative walks [14]. The fact that the participants were split is a good indicator that providing complementary modalities can be of value to suit personal preferences regarding meditation practices. Interestingly, when asked about the quality of the system's graphics, none of the participants mentioned the augmented sandbox; they only considered the VR as being a graphical display. This indicates that using the physical world as a support can make technology more approachable, if not transparent. This is of special interest given the demographics (middle aged females, two of them explicitly stated their reluctance towards technology before starting the study).

Not all the users saw the SAR and VR components of the systems as parts of a whole. Notably, they saw discrepancies between what they thought they were building in the sandbox and what they witnessed in VR. The users that did see a connection (4/12) found the parts complementary, and highlighted being able to create the virtual world from the real one. The sea was mentioned as the strongest link between real and virtual. Visiting the virtual world can also increase the impact of the projected augmentation: one participant mentioned she could not understand the cloud shadows on the sandbox until she visited VR, and that after she imagined the clouds floating above the real sandbox.

Multisensory Experience

We were interested on how the participants felt about the multisensory aspects of the system, namely the tactile, visual and auditory components.

All the participants enjoyed playing with the sand. They were particularly pleased by the texture of the white polymeric sand. Similar to the experts (E2_Psychomotor, E4_Psychologist, E5_Buddhist), several of them felt that playing with sand had a "grounding" effect, beneficial to their mindfulness. We also had comments about how shaping sand was a freeing activity, reminiscent of when they were children (a known aspect, used in Sandplay [25]). We provided samples of alternative materials. After trying the polymeric sand, the participants were not particularly inspired by the proposed substitutes, even regular sand. On the other hand, they found the idea of using pebbles or rocks an interesting option to create heterogeneous landscapes, such as in traditional zen gardens.

When asked if they were interested in customizing the appearance of the terrain, both the texture or the moment of the day or year, most participants liked the idea, but the ones with experience in mindful meditation were fast to notice that too much customization would be counterproductive for mindfulness, since it would not exercise their acceptance. They instead considered the possibility of an initial parametrization, and then letting the garden evolve slowly. This matches with the opinions gathered from the experts.

The participants were very pleased with the sea sound and being able to control it with the breathing, and felt it was synchronized with their inner state (9/12). They presented mixed emotions regarding the animal sounds: two of the participants, with backgrounds in music, found the overall sound-samples too monotone, and suggested adding a richer variety. This could be addressed using procedurally generated soundtracks.

For the study, the system layout was designed so that the participants sat comfortably on a rigid puff, while facing the sandbox that was placed over a table. Several participants found this position unusual for meditation, and asked if they could sit on the floor, or with their legs crossed. One participant also asked to move to a nearby couch for the VR session. Even when we tried to provide a comfortable environment for the participants, it would be interesting to see the reception of the system in a more ecological context.

Other Comments

Even when sensors we used were not designed for comfort, the participants did not mention them as inconvenient. The breathing belt limited the user's movement, which was not a problem while sitting. This could be still addressed using sensors such as Spire[2].

Finally, some participants confirmed what we observed on the questionnaires: the system created a sense of calm and feeling centered, in particular thanks to the sea and the sand. One of the participants (mindfulness meditation practitioner) sent us an email hours after the session to thank us, and commented she felt more relaxed during her work day. This might be caused simply because we provided a calm context to take a break from their routine, nevertheless we find these results promising.

Study Limitations

Even when the system was designed with novices in mind, the study was conducted with initiated meditators. The rationale behind this decision was that we first wanted to get feedback from practitioners to make sure that our design (and the use of technology) was not antithetical with their practices, to complement the feedback from experts. Even when we used questionnaires to measure the impact of the system, our main interest was to know more about their subjective experience. The preliminary results seem to indicate we are on the right track, laying the bases for a long term study.

Mindful meditation training requires longer periods of time, and measuring the impact of the system would require following novices along the training process. In the future we would like to conduct a long term study with novices, which will include a control condition, in collaboration with the mentioned meditation teachers. This would be vital to determine if the system can help or complement existing mindfulness exercises.

CONCLUSION

We presented Inner Garden, a mixed reality system that leverages Tangible Interaction, Spatial Augmented Reality, Virtual Reality and Physiological Computing in order to support mindful experiences. Our design considerations were based on the literature, complemented and validated with feedback of experts. Finally, we tested the system with meditation practitioners of different levels of experience (from initiated to daily meditators), which found the design engaging while also being well suited for mindfulness. Preliminary quantitative results seem to indicate that the system foster a calm and mindful state on the users.

We envision Inner Garden as an ambient device that would both provide a gentle reminder to practice mindfulness in daily life – like a plant that requires watering in an apartment – and a compelling tool to support mindfulness exercises. One of the main challenges will be keeping the system engaging, for example by introducing subtle changes over time such as seasons. Another interesting dimension to study is the potential of such a medium for social interaction around well-being. For example, multiple members of the family could take care of the same garden together, thus taking care of each other in the process. Both E1_Teacher and E3_MBSR perform group meditations as part of their practices and were interested on how it will be extended for multi-users, and explicitly proposed their interest to install the system on their practice. They were especially interested in its use to introduce novices to the practice of mindfulness. In the future we would like to study these aspects with their collaboration.

In the end, Inner Garden was not designed as the sole source of mindful experiences, but as an engaging way to pay attention to foster body and breath awareness. It serves as a first introduction to mindfulness, and ideally leads the users to train and develop a mindful perspective that will extend outside the garden, into their everyday life. For these purposes, tangible interaction is a promising approach. It has this interesting property of not looking like "real" digital technology, being closer to our physical and humane selves. Because of this, we believe that tangible and reality-based interaction [22] provide interesting approaches to the emerging field of positive computing.

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