Mediated Atmospheres: A Multimodal Mediated Work Environment

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Atmosphere - the sensorial qualities of a space, shaped by the composition of light, sound, objects, people, etc. - has remarkable influence on our experiences and behavior. Manipulating it has been shown to be powerful, affecting cognitive performance, mood and even physiology. our work envisions and implements a smart office prototype, capable of digitally transforming its atmosphere - creating what we call *Mediated Atmospheres* (MA) - using computationally controlled lighting, video projection and sound. Additionally, we equipped this space with a modular real-time data collection infrastructure, integrating a set of biosignal sensors. Through a user study (N=29) we demonstrate MA's effects on occupants' ability to focus and to recover from a stressful situation. Our evaluation is based on subjective measurements of perception, as well as objective measurements, extracted from recordings of heart rate variability and facial features. We compare multiple signal processing approaches for quantifying changes in occupant physiological state. Our findings show that MA significantly (p<0.05) affect occupants' perception as well as physiological response, which encouragingly correlate with occupants' perception. Our findings is a first step towards personalized control of the ambient atmosphere to support wellbeing and productivity.

CCS Concepts: • Human-centered computing \rightarrow Ubiquitous and mobile computing systems and tools;

General Terms: Design, Human Factors, Experimentation

Additional Key Words and Phrases: Ubiquitous Computing; Smart Office; Face Tracking; Heart Rate Variability; Perception; Wellbeing; Adaptive Building; Multimodal; Restoration; Productivity; Augmented Reality; Mediated Atmospheres

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1 INTRODUCTION

Our senses constantly perceive and interpret information about our surrounding environment. Often unconsciously, textures, colors, shapes, sounds and light find their way into our cognitive schema and serve as cues to recall skills, knowledge, feelings and behaviors. This phenomenon sparked researchers' interest for decades, particularly for its implications to cognitive performance, health and wellbeing. Art and architecture are prominent examples of attempts to harness this latent power of the physical environment for designing behaviors, perceptions and experiences.

In this paper we explore a concept for digitally augmenting the atmosphere of an office workspace. We use multimodal media – video projection, lighting and sounds – to computationally create different atmospheres in the workspace. These atmospheres are created by the harmonious composition of all the aforementioned media outputs. We name these compositions *Mediated Atmospheres*. Sensing and computation mediate between occupants' actions and the atmosphere. Mediated Atmospheres are designed to create perceptually different experiences for occupants. Our choice of digital multimedia allows the workspace to dynamically toggle between

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different atmospheric scenes. This enables selecting the atmospheric scenes not only according to occupant preference, but also according to different working activities. Such an approach is well suited for the fast-paced dynamic nature of modern working schedules. It also maps well to common trends such as unassigned temporary desks.

Such a technology may address major concerns in contemporary workspaces, in particular for knowledge workers. Recent reports indicate a steady decline in workplace satisfaction over the past decades, which has implications for reduced productivity and motivation [24]. Conversely, employees who have the freedom to choose where to work exhibit opposite trends. They were found to be more satisfied, more productive, and more engaged [24, 56]. Especially today, with continuous distractions from many streams of digital information and increasing workstation density, workers need a space to focus and recharge in order to work effectively [24]. Working remotely is often not a viable solution, as it hinders organizational collaboration and limits necessary employees access to company resources.

A digitally controllable atmosphere in the workspace is, however, only the first step in a broader vision. Recent advancements in sensing technologies and machine learning resulted in notable progress in activity detection, as well as in affective state prediction. We accordingly envision workspaces that can self-regulate on the basis of an occupant's activities and affect in a closed-loop fashion. Dynamic and digital control presents an opportunity to synchronize the workspace experience with the ever changing requirements of today's workers. The closed loop control can be designed to optimize various purposes, such as productivity, collaboration, health or even wellbeing.

We imagine a workspace that, when asked, can instantly trade the engaging diligence of a library with the liberating sensation of a stroll through the forest— a workspace that can replicate the invigorating tension of a control room or the restorative qualities of a beloved childhood hideaway. We foresee such a workspace gaining intelligence through affective sensing, identifying environments that either enhance performance or support our health and wellbeing. As a result, the workspace might suggest the atmosphere of a local coffee shop or an artifact-strewn artist's living room when it is time to spark creativity, and the atmosphere of a study when it is time to maintain focus. The workspace might integrate brief nature escapes into our workday, supporting us in our effort to balance our schedule and physiological needs and create more sustainable, healthier routines. Looking ahead, we envision more complex applications that would use the ambiance to strengthen memory and support learning activities.

This vision aligns well with the outlook for intelligent buildings in Ubicomp - striving to leverage pervasive sensing and context recognition to create meaningful interactions with the built environment. Our research is distinguished from existing work in this area by its focus on affective sensing and multimodal media outputs rather than unimodal ones. Additionally, it is unique in its application effecting work experiences rather than providing conveniences [47] or information display [51]. Like much of the work of Ubicomp, we seek for this technology to function in the background, inviting the users' attention rather than taking it away from their tasks. We aim to clarify how such technology could find a place in everyday work life.

To explore this concept, we have built a fully functional prototype. Relevant related work is discussed in Section 2 and the prototype itself is described in details in Section 3. Our prototype uses state of the art media output technologies to augment the physical characteristics of the space. Through these, we project content composed from existing, real world environments. We focus on atmospheric scenes which differ in their perceived potential to foster focus and stress recovery. These qualities are key aspects which affect occupants' wellbeing and were identified as the main work modes that commonly require changing of work settings [24, 65]. Accordingly, the atmospheric scenes we have composed use images and sounds of nature, building on Environmental Psychology research, which emphasizes nature's role in focus and stress regulation.

Our prototype is the first in many steps we intend to take in realizing our vision. It is an example of a typical work setting, which is suitable for tasks such as computer work, one-on-one meetings and tele-conferencing.

Before considering other settings, we chose to utilize this particular setup for an experience research study on individual work. We include this study in our paper, assessing the effectiveness of our design and alluding to the feasibility of our vision. The experimental protocol, methods and results of our study are described in Sections 4 and 5 respectively. Our evaluation is inspired by studies in Environmental Psychology as well as music research [42, 45]. We adopt a unique method, which combines subjective perceptual measurements for focus and stress restoration, alongside objective measurements extracted from physiology, focusing on Heart Rate Variability (HRV) as an indicator for stress recovery. We evaluate multiple ways to quantify changes in occupants' physiological state using aggregated statistics and probabilistic modeling. This analysis aims to identify a metric for real-time evaluation of user response in relation to the synthesized atmosphere. A similar analysis can be utilized by future applications that wish to detect and respond to occupants' stress and focus. We conclude by discussing our results In Section 6.

Through the prototype and our user study we learn about the physical design, develop our evaluation and data analysis methods, and identify salient sensor features to measure potential effects. We intend to build on these learnings in our future work. There are still many open questions we wish to answer. For instance, we wish to investigate how workers experience Mediated Atmospheres in a more natural settings – performing tasks in the space that were not designed by us. We aim to study if and how design attributes such as timing, sequencing, and repetition affect the work experience or outcomes. We also wish to apply our design learnings to additional work spaces, such as open plan offices or larger conference rooms. We believe our agile software design and sensing system can easily be ported to these settings. Though the form of augmentation may change, we believe that many elements of the physical design can similarly be applied. Finally we are interested in testing context-aware control agents that control the atmosphere by either predefined heuristics or by models learned from individual responses. These future experiments might provide insight on preference construction [30] and interactivity [5].

In this paper our main contribution is the presentation and development of new techniques to enable a room to transform itself, via projection, lighting and sound, to responsively and adaptively influence a user's inferred affective state. We evaluated the effectiveness of the prototype system through a human subject study and we compared multiple signal processing approaches.

Contributions

- Introduced a prototype system which is capable of dynamically mediating its atmosphere as well as monitoring and processing occupants' physiological signals in real-time.
- Evaluated Mediated Atmosphere's effects on occupants' ability to focus and restore from a stressful situation, and related self-reported and physiological responses.
- Compared multiple signal processing approaches for quantifying changes in occupants' physiological state.

2 RELATED WORK

Specific attributes of the surrounding environment have been shown to support memory, foster creativity, enhance sensitivity to details, and balance cognitive load [12]. For instance, McCoy and Evans identified physical characteristics that facilitate creative performance, such as natural materials and a limited use of cool colors [43]. Mehta et al. found that moderate levels of noise, like the ambient sound of a coffee shop, facilitates abstract processing [44]. Mott et al. observed that classroom lighting led to better learning performance, when it was tuned to the students activity [46]. Motivated by such discoveries, a recent revision of the theoretical framework of cognitive load has even reconceptualized the physical environment as one of the main three causal factors determining cognitive processing [12].

The environment has additionally been shown to manage important aspects of psychological affect. Light, for example, has measurable effects on mood [6, 39], work motivation [9], and social behavior [41]. In a complex

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interplay, human physiology also responds to its surrounding environment either directly or by proxy through psychology. Noise, for instance, commonly triggers excitation, which with prolonged exposure is likely to cause chronic-stress [34]. Light, as a non-visual signal, has acute effects such as increasing subjective alertness, enhancing psychomotor performance, and suppressing pineal melatonin production, a hormone that maintains the body's circadian rhythm [21, 22, 26]. Experiences of nature exhibit healing and restorative qualities. Even minimal exposure to plants has been demonstrated to facilitate stress regulation and physical recovery [25]. For these reasons, the restorative effects of natural environments have long been of special interest in Environmental Psychology [37].

Over past the years, ideas around intelligent building control have also been extensively researched. One of the major themes was to increase energy efficiency and occupant comfort through personalized control. Prior research investigated how different factors influence human comfort. Factors such as thermal, visual, and aural comfort as well as indoor air quality have been identified to contribute to Indoor Environment Quality (IEQ) [15, 23]. Accordingly, the potential of automated control of these parameters, e.g. HVAC and lighting, was researched to improve energy consumption and comfort. In lighting systems for example, researchers were able to achieved energy savings through presence and activity detection. These utilized technologies such as wearable sensors [1], sensor networks [54], and multi-color lighting [10]. Similar work investigated ways to incorporate personal preferences in these automatic controlling schemes, for example for HVAC control in office environments [19]. In the home environment, researchers have demonstrated numerous solutions for learning user routines and context – typically learning location, identity, schedules and in some cases even particular occupant activity [16, 47, 50, 63]. These were then leveraged to automatically trigger home appliances, in an attempt to increase users' comfort.

Although sympathetic response detection has been used in biofeedback-driven meditation/relaxation systems for decades [27], a new generation of applications has been enabled by more advanced context recognition methods that incorporate affective state. Examples outside the domain of building control include cars that respond to driver fatigue [35] or games for relaxation training [11]. Physiological information can also benefit user preference modeling for smart homes [40]. The Sonic Cradle and ExoBuilding are examples of physiological signals controlling the build environment. In the Sonic Cradle the user's respiration pattern generates sound to help her to immerse in a meditative state [61]. The ExoBuilding transforms its physical shape to visualize several streams of physiology recordings [53].

With the growing availability of digital infrastructure, users increasingly encounter interfaces both at the center and the periphery of their attention. A focus of the latter has been environments that aim to subtly influence occupants, such as those with ambient displays [33]. Similarly, research in Spatial Augmented Reality has found innovative ways to include the physical home environment for entertainment and remote collaboration to create a more immersive experience [7, 59]. Another expansion of this research field is into accommodating further sensory modalities, e.g. mechanical, haptic or even olfactory manipulation [3, 48].

3 PROTOTYPE SYSTEM

The prototype was implemented in a windowless rectangular room, 4.2 m by 2.8 m with a ceiling height of 2.6 m. The physical layout of the room is sketched in Figure 1. This space was initially constructed with only controllable lighting capabilities used in previous work [2, 65], and further extended with projection and sound output for Mediated Atmospheres.

3.1 Design Criteria

In order to conduct research on work scenarios, it is a requirement that Mediated Atmospheres does not impair the use of familiar work tools. For instance, the user should be able to comfortably use their personal computer, write and sketch on paper, have conversations with colleagues, etc. This requirement excludes the use of wearable

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Fig. 1. Physical layout of the room.

Virtual (VR) and Augmented Reality (AR) systems. However our research findings could be applied to such technologies if they become more widespread and usable in the future.

We consider lighting as a central factor of our design, given its wide-ranging effect on the human body. While display technologies can create immersive illusions, illumination technologies provide high quality light, e.g. high dynamic range, and Color Rendering Index. A combination of both therefore covers the visual and non-visual influence of light. The feeling of presence or immersion is another important factor [32, 55]. We therefore synchronize light and visual images with sound. Sound is able to alter our sense of the environment beyond the limited visual window, for example to convey the spaciousness or openness of a place [28]. Accordingly, our prototype integrates these output capabilities in the room and furniture.

The space design process was guided by frequent exchange with office furnishing and lighting professionals. By doing so, we expect our research to be relevant to modular office and cubicle design in the future.

3.2 Outputs

20 individually controlled **light** fixtures were installed in the ceiling. Each fixture has 5 channels, Red, Green, Blue, Warm White and Cold White. Six wall-washing luminaires (*Colour Kinetics, Skyribbon Wall Washing Powercore*) are installed along the long edges of the room and light the walls to the occupant's left and right. Two downlight luminaires (*Colour Kinetics, Skyribbon Linear Direct Powercore*) are installed in the center, directly above the occupant's workstation.

There are two options of **sound** output in the current prototype. We installed an ambisonic sound system using four speakers. If the direction of sound is preserved in the recording, the speaker array is able to reproduce the spatial sound experience. However, this kind of output does not allow the control of ambient noise. Therefore, as an alternative, sound can be delivered through a pair of noise canceling headphones (*Bose, QuietComfort*). Headphones were used during the study.

For **video projection** we use a high-luminosity output projector (*NEC, NP-PA571W*) with short throw lens (*NEC, NENP30ZL*). A custom rear projection display was built using a 1.83 m by 0.76 m light-diffusing acrylic. Without projection, the display is white and opaque, mimicking the aesthetics of a modern cubicle's wall-divider. The display is placed in front of a working desk and is leveled to the height of a sitting person. We built a wooden base to hold the projection surface without a frame, which gives it the appearance of an integral part of the working desk see Figure 4.

Prior to the production, we tested a wide range of possible displays with potential occupants and content designers. The current design attempts to reconcile the main feedback points our users surfaced. For example, the display was intentionally cropped not to follow familiar display ratios, e.g. 16:9 or 4:3, which tended to

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Fig. 2. Top-level design of the Scene Control Server.

reduce occupants' immersion and resulted in lower effectiveness in creating an association with the displayed environment, compared to the chosen format. We also intentionally placed the display towards the front of the desk, covering most of the occupants' peripheral vision. Horizontal and vertical viewing angles are 100^o and 53^o, respectively.

3.3 Scene Control Server

A **Scene Control Server** implemented in Python facilitates real-time digital control of all output capabilities. It manages seamless fading transitions between scenes. Furthermore it provides a Websocket interface, which allows us to quickly prototype web-based applications for manual or sensor-driven control. Using this interface, we have developed a set of tools for scene design.

The scene library currently contains over 30 atmospheric environments based on real places. These include beaches and nature landscapes, indoor spaces such as libraries, cafes and museums, and scenes of metropolitan cities, train rides and even a rollercoaster ride. These scenes were chosen to cover a wide range of effects and perspectives. Each scene contain video and sound data, lighting configuration and meta information of key characteristics.

For lighting design, we introduced the concept of virtual light sources which separate the desired lighting result from the physical lighting system layout in the room. Virtual light sources map onto our existing fixtures and can be placed in any position, with any color, intensity, and size. Using this, we can apply the same virtual light configurations in a different space by simply changing the room model, which defines the mapping of virtual lights to fixture ID and RGB values based on the position of lighting fixtures in the space.



Fig. 3. Top-level design of the Sensor Collection Server.

3.4 Sensor Collection Server

In parallel, the **Sensor Collection Server** manages all incoming data steams and facilitates real-time data processing and logging. When the service is executing, it initiates connections with a configurable list of sensors and begins harvesting data samples from all of them. External applications can register to the service, obtaining a processed version of the data samples from one or more data streams.

We built the infrastructure as an asynchronous code library implemented in Python, based on the Twisted library [20], following a Reactor design pattern [52]. This design pattern implements an event driven scheme, in which multiple data streams are multiplexed into a single computation context. Whenever sufficient data is available on any of the streams, an appropriate event handler is called to process it. Processing can be done in layers to improve concurrency, breaking it to smaller sequential event handlers, which trigger each other also via events. A load balancing mechanism prevents starvation, assuring that all streams receive adequate processing time.

The current prototype supports *Zephyr Bioharness 3* [64], a physiological monitoring chest strap, *Empatica E4*, a wrist-worn biosignal monitoring device, and *Intraface* [17], a facial feature tracking software library. Supported measurements are summarized in Table 1. A camera (*Logitech, Quickcam Vision Pro*) on the desk captures videos

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Table 1. Sensors and their featured measures.

Sensor	Measurements (Reporting Frequency)
Zephyr Bioharness 3	Heart Rate (1 Hz), RR Interval (18 Hz), ECG (250 Hz), Respiration Rate (1
	Hz), Breathing Waveform (25 Hz), Posture (1 Hz), Activity Level (1 Hz), Peak
	Acceleration (1 Hz), 3 Axis Acceleration (100 Hz), Sensor Confidence, Device
	State and Debugging Information (1 Hz)
Empatica E4	3 Axis Acceleration (32 Hz), Blood Volume Pulse (64 Hz), Inter Beat Interval,
	Electrodermal Activity (4 Hz), Skin Temperature (4 Hz)
Intraface	Coordinates of 49 facial feature points, describing the eyebrows, eyes, nose
	and lips
	Vector estimating occupant's 3D head orientation
	Vectors estimating the 3D viewing orientation for each of the occupant's pupils
	Intensity predictions of 6 emotions the occupant expresses (neutral, angry,
	disgust, happy, sad and surprised)

of the occupants. Videos are recorded and processed in real-time using the Intraface code library at approximately 10fps with a resolution of 1280 by 720 pixels.

4 EXPERIMENT

The goal of the experiment was to assess the effect of Mediated Atmospheres on the perceived ability to focus and restore from a stressful situation, and to evaluate its influence on physiology.

4.1 Experiment Design

To test *Mediated Atmospheres' effect on users' perception*, we adopted a repeated-measures design, with type of atmosphere as a within-subjects variable. Subjects were exposed to five atmospheric conditions, which are described in detail below. We collected perceptual response through a user survey for *Perceived Restoration Potential* (PRP) and *Perceived Focus Potential* (PFP). Perceived Focus Potential indicated a person's subjective judgment of a scene's suitability for work tasks which require mental concentration. Perceived Restoration Potential indicated how suitable a scene is for restoring from a stressful situation. The measures are described in detail in section 4.5. To determine any significant changes, Friedman's Test with post-hoc comparisons using the Wilcoxon Signed Rank Test was conducted for each measure. The analysis was carried out using MATLAB's Statistics Toolbox.

For the analysis of physiological effects, we hypothesize that *there is consistent difference in physiology indicating* a stress reducing or focus enhancing effect (1) between restorative and non-restorative and (2) focus and non-focus Mediated Atmospheres. In order to examine physiological effects in relation to subjective perception, and to take personal bias into account, each physiological measure was labeled according to its associated perceptual rating, which was obtained through the survey introduced above. A scene with PFP rating above average was considered a focus scene. Otherwise it was labeled as non-focus. A scene with PRP rating above average was considered as a restorative scene and non-restorative otherwise. A series of paired t-tests, one for each physiological measure, was performed to evaluate the significance of mean differences between the two levels of restoration and focus.

Subjects' physiological responses were recorded in all five test conditions. In each condition, participants were asked to perform a sequence of cognitive tasks sitting in front of a laptop computer, including a graduate-level ETS GRE reading comprehension assignment [18], followed by a restorative break. We chose these tasks to simulate a focused and stress-eliciting work situation and the recovery from it. We intentionally combined the

two situations in order to test our processing algorithm for alternating work activities. Our processing algorithm is required to identify physiological changes introduced by the scenes despite larger fluctuations caused by the user's activity. This is necessary for future experiments with unscripted activities.

Analysis was carried out using a small subset of the recorded physiological features. Through a preliminary analysis, we identified three most salient features: Heart Rate Variability, Head Orientation and Neutral Facial Expression. In addition, we also conducted the Necker Test to measure participants' ability to focus their attention. The features are explained in detail in section 4.6.

4.2 Conditions

We designed five atmospheric scenes. Each scene introduces a different context that is often associated with focus or restorative activities. Their key characteristics are summarized in Table 2. The video lengths vary, but they are all longer than the duration of the study. If a video reaches the end, it loops to the beginning.

- **Forest** The video projection shows a forest in autumn. A clear, shallow mountain stream flows though a dense, partially red-colored forest. There is no camera motion. The perspective suggest that the viewer is resting, elevated over the stream. One can hear the sound of the river and occasionally birds in the background. Low intensity, warm lighting completes this scene. Two virtual light sources in the center of the ceiling correspond to the forest opening and direction of lighting in the video.
- **Library** The video shows a study room in a university library. A number of students are present. They are sitting at tables and studying independently. There is no camera motion. The viewer appears to be sitting at one of the tables in the library. One can hear the ambient sound of the space, such as movements, or when someone enters or leaves. High intensity, white light characterizes the ambiance of the room. A virtual light source in the center of the ceiling corresponds to the fluorescent ceiling lights in the image.
- **Kites** The video shows three kites against the background of a blue sky. The horizon is not visible. Each kite has a unique shape, flying speed and trajectory. The third kite appears and disappears from the screen depending on its movement. There is no camera motion, but compared to the Library and Forest scene, there is significantly more visual action. The camera perspective suggest that the viewer is resting and looking up to the sky. One can hear ocean waves crashing in the background. For this scene we choose cold, high intensity, primarily indirect lighting which complements the color and openness of the sky.
- **City** The video shows a walk though the Shibuya district in Tokyo, Japan. The camera moves steadily at walking speed through crowds of pedestrians. The video captures the activities of a busy walking district with colorful billboards, shops and buildings from a first-person-perspective. One can hear the sound from the street, some illegible speech, music coming from the stores, etc. We choose a mix of direct and indirect, high intensity white light, which corresponds with the weather in the video image.
- **Neutral** Finally we created a "Neutral" scene, which is the office without augmentation. The projection screen is white, the projector displays a black screen. Lighting is uniform, white and at medium intensity. There is no additional sound. This scene represents the original office context.

4.3 Participants

The population of interest is office workers. The experiment panel therefore consists of university students and local office workers, N = 29, 40% Female. On average, participants were 31 years old (M = 30.8, SD = 6.7).

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	Test Conditions								
Characteristic	Forest	Library	Kites	City	Neutral				
Movement in video	Low	Low	High	High	None				
People or Buildings in video	No	Yes	No	Yes	No				
Nature in video	Yes	No	Yes	No	No				
Light Color Temperature (K)	3500	5500	9000	6500	6500				
Horizontal Illumination on the Desk (lux)	250	1000	800	1000	350				
Sound	Forest, river	Ambient sound of the library (e.g flipping pages)	Ocean waves	Ambient sound of the city (e.g. illeg- ible voices)	None				
Expected Restoration	High	Low	High	Low	Low				
Expected Focus	High	High	Low	Low	High				

Table 2. Conditions and characteristics.

4.4 Procedure

Both perceptual and physiological recording were done in one sitting, which took approximately one hour and was divided into five identically-structured sequential sessions. In each session, the participants were exposed to a different, randomly selected scene. Each sitting began with a tutorial during which the study personnel explained each part of the session. Subsequently, the participants were left alone in the workspace, and a website guided them through the experiment. The website also controlled timing of the transitions between the scenes in the room and collected the participants' inputs.

The procedure of the tasks and their timing are visualized in Figure 5. In order to disconnect the sessions and to avoid possible novelty effects at the beginning of each session, participants were exposed to the Neutral scene for 30 s and the tested scene for 1 min.

4.5 Measures of Perception

For the assessment of perceptual effects, we used direct rating. All ratings used a five-point Likert scale raging from -2 ("very low") to 2 ("very high"). Participants rated each atmospheric scene on 6 variables. Two questions asked the participants to imagine themselves in a particular situation and assess how suitable the rendered scene is for it. This approach was inspired by prior research, such as [31]. The first question described a situation when one is full of energy and has to direct effort towards a new task. This rating measured the Perceived Focus Potential (PFP). The second question described a situation when one is recovering from prolonged mental effort. The remaining questions in the survey were based on the revision and verification of the Perceived Restoration Score Questionnaire done by [49]. Accordingly, the five facets of a restorative environment are: Compatibility, Coherence, Being-away, Fascination and Scope. Coherence was measured inversely, asking the participants how chaotic and confusing the scene is. The Compatibility was phrased to focus on the occupant's personal preference and liking. The mean of all restoration-related ratings defines the Perceived Restoration Potential (PRP). A copy of the survey with the specific phrasing is affixed.

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(1) Neutral





(3) City

(4) Forest



(5) Library

Fig. 4. Images of the test conditions

4.6 Measures of Physiology

4.6.1 *Heart Rate Variability.* Heart Rate Variability (HRV) is an established psycho-physiological measure for stress development and restoration e.g. in [8, 57]. High HRV is generally believed to indicate parasympathetic regulation [8]. Using the Zephyr Bioharness 3 [64], we recorded RR, which measures the time interval between

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	Sitting S	Structure:										
	Tutorial	Sess	sion 1	Session 2	Session 3	Session	4 5	Session 5				
	Session	Structure:										
Clock:	30 Sec.	1 Min.		3 Min.	3 Mir	ו.	30 Sec.	Unlimited				
Task:	W	/ait	Readin	g Comprehension	Break (Stress I	Restoration)	Necker	Survey				
Scene:	Neutral		Randomly Selected Scene									

Fig. 5. Schematic illustration of the study protocol. Each participant was invited to a single sitting consisting of six identical sessions. Sessions were structured as illustrated above.

consecutive heart beats. This signal was generated on the device using the ECG waveform sampled at 1000 Hz. For the calculation of HRV, the recorded RR interval series was converted to a equidistantly sampled series by cubic spline interpolation. The resulting sample rate is 18 Hz. We used the standard deviation of RR intervals (SDNN) method to compute HRV. SDNN was calculated for consecutive overlapping sections of 1 min of the resampled RR data. We then applied a moving average filter with a window length of 10 s. The result was set to the right edge of the window.

4.6.2 *Head Orientation.* Using the head orientation information we aim to estimate where participants directed their visual attention. A lifted head position was associated with attention towards the projection screen, which is tall and further way. Accordingly, looking at the table or laptop computer resulted in a dropped head orientation. A restorative environment naturally draws attention [37], whereas a focus environment should not create any distraction. Therefore, we expected a difference in visual interest between the different conditions. Participants' head orientation was generated by Intraface.

4.6.3 Facial Expression. Facial expression indicates whether the participant exhibited emotional changes during the experiment. We chose the Neutral feature, because we were most confident about the interpretation of this feature compared to the other available emotional features. This feature was reported as a confidence level between 0 and 1, with a value of 1 indicating a confident detection of Neutral expression. It was therefore not normalized per person in post processing.

4.6.4 Direct Attention. The Necker Test [13, 14], which is widely administered in attention research, attempts to measure one's capacity for direct mental effort. Participants were presented with a wire-frame cube which can be perceives in two different orientations (see Figure 6). When viewed for prolonged period of time the cube spontaneously reversed its perceived orientation. The time period over which one can sustain the cube in a particular orientation has been shown to be correlated with one's ability to direct attention [58]. We recorded the number of reversals through mouse clicks. An increase in reversals suggests a decrease of the participant's ability to direct their attention in the rendered scene.

4.7 Signal Processing

We must define an appropriate metric from the physiological signals, which concisely describes the main effects of Mediated Atmospheres. A wide range of such metrics has been previously proposed in the literature. The simplest ones report aggregated statistics (such as median, mean and standard deviation) of the physiological signals and



Fig. 6. Necker Test. Participants were presented with the leftmost image. The following images illustrate the two possible perceived orientations.

compare those between the different experimental conditions. Other approaches attempt to characterize trends in the signal. Kahn et al. measured heart rate recovery by fitting a regression line to the first 60 seconds of each experimental activity [36]. Such an approach would be very limited in the context of our desired system.

Physiology is responsive to many psychological influences besides the physical settings. Cognitive workload, for instance, is a varying factor, which is very likely to affect physiology even more than the physical settings [62]. Furthermore, physiology and physiological regulation are highly personal and state dependent. Autonomic heart rate regulation, for example, can vary greatly among individuals with different training routines [60]. Even within individuals, simply drinking a cup of coffee can influence the recorded physiological signature [4].

To examine possible approaches we experimented with multiple metrics; the commonly used mean value and metrics based on probabilistic modeling, an approach that potentially could describe multiple trends that may arise during varying work modes.

4.7.1 Processing of Physiological Measures. In the following description, a sample is a time series signal that contains one physiological measure of one session. It is therefore associated to a specific subject and atmospheric scene and has the length of 8 minute or longer. Each sample was summarized into multiple metrics for comparison, e.g. (1) mean, (2) probability to be greater than mean (Prob. > 0), and (3) probability to be more than one standard deviation greater than mean (Prob. > 1). For the Necker Test only the mean values were compared.

We built a model for each sample, where we treated the data points as random variables, and established a probability density function (pdf): p(x). We used Kernel Density Estimation (KDE) with a Gaussian Kernel to construct the pdfs from the observations. This pdf can be interpreted as an estimation of what would be the probability to observe physiological state x. The probability that an expected physiological measure will fall within a certain range, $p(x \in [a, b])$, is the area under the curve of the constructed pdf. Given that x = 0 is the average level of a z-score sample, the probability of a physiological state higher than average is $p(x \in 0, \infty]$) and the probability of a to be more than one standard deviation greater than average is $p(x \in 1, \infty]$). These probability estimations were used for the analysis of HRV and Head Orientation. For Neutral Facial Expression we computed the likelihood of a confidence level above 0.5.

Post experiment, all recordings were inspected visually to identify and sort out sessions with sensor failure. Outliers that were higher than 5 times the standard deviation of the specific sample were removed. Unless otherwise specified, samples were normalized per person. As established earlier, we expected differences of physiological signal among the population. To make the comparison more meaningful, we transformed each data point to its z-score. Before we computed two metrics, any data points that were recorded during the 30 s Neutral time and 1 min adjustment time at the beginning of each session were removed.

5 RESULTS

5.1 Effects on Perception

Perception differed significantly (p < 0.05) among the atmospheric scenes for both perceived focus potential (PFP), $\chi(25) = 29.8$, $p = 5.33 \cdot 10^{-6}$ and perceived restoration potential (PRP), $\chi(28) = 42.3$, $p = 1.45 \cdot 10^{-8}$.

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Table 3. Perception test mean scores (M) and standard deviation (SD) of five atmospheric scenes. Scenes that were perceived significantly different than Neutral are highlighted.

	For	rest	Library		Kites		Ci	ty	Neutral	
	M	SD	M	SD	M	SD	М	SD	M	SD
Perceived Focus Potential (PFP)	1.07	0.96	0.76	1.18	0.46	1.40	-1.00	1.25	0.64	1.13
Perceived Rest. Potential (PRP)	1.21	0.72	-0.06	0.87	0.67	0.84	0.53	0.99	-0.44	0.99





(3) Boxplot of perceived focus (central mark - median; box - 25th and 75th percentile; whiskers - maximum and minimum which are not considered outliers)

(2) Mean scores of perceived focus and restoration visualized in a x-y-diagram. The ellipses represent personal variances in the focus-restoration-space. The error-bars have the length of two standard deviation.



Post-hoc comparisons of individual mean differences showed that PRP for Forest, Kites, and City were significantly (p < 0.05) higher than for the Natural office atmosphere. There was also significant difference in PRP between Forest and Library. Concurrently, the PFP for City was significantly reduced compared to all other tested scenes.

These results suggest that our prototype of Mediated Atmospheres is able to affect the user's perception of the office's suitability for restoration and focus as defined by our measures. Specifically, Forest and Kites atmospheres were considered as suitable for both restorative and focused activities. On average, the City scene was considered as promoting restoration but not focus. Library and Neutral scenes were considered as less restorative, but suitable for focus, see Figure 7. These trends overall agree with our design-intentions. However, high variance indicates strong personal and context-specific differences in atmosphere preference.

5.2 Effects on Physiology

5.2.1 *Heart Rate Variability.* Paired t-tests revealed significant (p > 0.05) differences between restorative and non-restorative scenes (labeled according to user ratings as defined in section 4.1) in all metrics: aggregated

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					HRV								
	Fo	cus	Non Focus					Rest.		. Non F			
	M	SD	M	SD	p	Diff. (%)		M	SD	М	SD	Þ	Diff. (%)
Mean	0.03	0.18	-0.07	0.20	0.17	140.9	Mean	0.08	0.15	-0.14	0.24	0.003	158.6
Prob. > 0	0.45	0.09	0.40	0.09	0.09	11.4	Prob. > 0	0.47	0.08	0.39	0.11	0.014	20.2
Prob. > 1	0.16	0.05	0.14	0.07	0.50	9.1	Prob. > 1	0.17	0.05	0.13	0.06	0.013	36.8

Table 4. HRV mean scores (M), standard deviation (SD), and difference between conditions.

Table 5. Head Orientation mean scores (M), standard deviation (SD), and difference between conditions.

		Head Orientation											
	Foc	us	Non Focus					Rest.		Non Rest.			
	M	SD	M	SD	Þ	Diff. (%)		M	SD	M	SD	Þ	Diff. (%)
Mean	-0.22	0.19	-0.01	0.33	0.016	-1504	Mean	-0.12	0.19	-0.24	0.23	0.11	50.0
Prob. > 0	0.38	0.08	0.43	0.11	0.021	-13.7	Prob. > 0	0.41	0.07	0.37	0.13	0.15	11.8
Prob. > 1	0.10	0.05	0.18	0.12	0.011	-44.7	Prob. > 1	0.14	0.05	0.13	0.05	0.011	62.0

Table 6. Facial Expression mean scores (M), standard deviation (SD), and difference between conditions.

		F	acial E	xpress	sion								
	Fo	cus	Non	Focus				Re	est.	Non	Rest.		
	М	SD	M	SD	p	Diff. (%)		M	SD	M	SD	p	Diff. (%)
Mean	0.64	0.25	0.57	0.24	0.042	10.7	Mean	0.60	0.27	0.63	0.25	0.31	5.1
Prob. > 0.5	0.65	0.25	0.58	0.23	0.040	11.1	Prob. > 0.5	0.61	0.27	0.64	0.25	0.31	5.4

mean HRV (t(28) = 3.2, p = 0.003), probability of high HRV (t(28) = 2.6, p < 0.014) and probability of very high HRV (t(28) = 2.7, p = 0.013). On average, mean HRV in restorative conditions were 1.5 times higher than in non-restorative scenes. HRV was also on average 20% more likely to be above personal mean and 36% more likely to be more than one standard deviation higher in restorative conditions (see table 4). There were no significant differences of HRV between focus and non-focus conditions.

5.2.2 Head Orientation. Participants' head orientation were facing significantly more downwards in focus than non-focus environments according to all three measures (Mean: t(23) = -2.6, p = 0.016, Prob. > 0: t(23) = -2.1, p = 0.021, and Prob. > 1: t(23) = -2.8, p = 0.011). For the two levels of restoration, the difference was only significant for distinctively lifted head orientation (Prob. > 1: t(20) = 2.8, p = 0.012).

5.2.3 *Facial Expression*. Neutral facial expression was significantly more often detected in focus than non-focus environments (Mean: t(23) = 2.2, p = 0.042, Prob. > 0.5: t(22) = 2.4, p = 0.040). This was not the case for the two levels of restoration.

5.2.4 Necker Test. Differences in Necker Test results were not significant, neither for focus nor restorative conditions. However, on average Necker results were lower (Mean and standard deviation of difference between conditions M' = -0.23, SD' = 1.01) in focus than non-focus environments and higher (M' = 0.25, SD' = 0.91) in





(1) HRV Time Series of one typical participant. Steady decline of HRV can be observed for all environments during the reading assignment. However the initial slope varies between atmospheres. Similarly, the speed and amplitude of HRV recovery are different among the scenes.



Fig. 8. Visualization of HRV of one typical participant. (1) Time Series Signal. (2)-(5) Estimated Probability Density Functions of Forest, Kites, Library, and City in comparison to the Neutral Setting. (6)-(9) Estimated Probability Density Functions for reading and break activities separately.



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(1) Head Orientation Time Series of one typical participant. During the reading assignment, Head Orientation in the City and Neutral setting were similar. In the Forest scene subject look up more often. During the break participant's head was lifted higher and more steady in the City Setting.



Fig. 9. Visualization of Head Orientation of one typical participant. (1) Time Series Signal, for visibility only two scenes are shown. (2)-(5) Estimated Probability Density Functions of Forest, Kites, Library, and City in comparison to the Neutral Setting. (6)-(9) Estimated Probability Density Functions for reading and break activities separately.

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restorative than non-restorative conditions. A follow up analysis to examine whether there were any notable differences for the five tested conditions revealed that participants performed significantly (p<0.05) better in the Library than the City scene (Wilcoxon signed-rank test: $X(26^1) = 44.0$, p = 0.022, t-test: t(26) = 2.53, p = 0.018).

5.3 Sensor Reliability

Heart rate monitoring worked reliably with 99.3% success. Only one sample was dropped due to missing data. A few samples of RR contained outliers that were removed according to the procedure describe above. In comparison, no sensor failure was detected for respiration, activity level, and posture.

Facial recognition depended on the presence of facial features in the image. This data stream was disturbed when the participant turned away from the camera, moved outside the frame, or when her face was partially occluded, for example by her hands. This limitation led to spotty and missing data. We dropped in total 37 sessions from 10 different participants, which accounted for 25.5% of all recordings, and used the remaining for analysis.

6 DISCUSSION

6.1 Effects on Focus and Restoration

The study results suggest that our prototype workspace and the design choices we have made successfully influenced participants' perception of the space's potential for restoration and focus. Accordingly, environments that were perceived as restorative also exhibited the desired physiological response. Furthermore, we identified two sensor features that corresponded to environments that were perceived as suitable for focus. This result is important as a first step to quantify the effect of our prototype. In previous research, the influence of restorative stimuli has varied depending on the specific setup [36, 55]. Furthermore, few studies have empirically investigated the relationship between restoration and preference [29]. Our results show substantial variance among participants' ratings and that physiological responses correlate with personal preference. This result confirms that personal appreciation for an environment had significant influence on restoration outcome. Our findings agree with previous work on the restorative effect of nature [37]. Prior research has shown that nature scenes are more restorative than urban landscapes. This is reflected in the overall trends in the participants' ratings on restorative than these were not perceived as being less suitable for focus. On average, Forest and Kites were rated as more restorative than the City scene, and the City scene as more restorative than the Neutral office.

Despite significant motion of the kites in the image, the Kites atmosphere was overall not considered distracting. The City atmosphere however, which has camera movement and peripheral image movement, substantially decreased focus potential. This is an indication that there is higher tolerance of movement, when it mainly occurs in the center of the visual field, such as in the Kite scene.

Because the Neutral office setting is already an environment that is conducive to focus, the tested atmospheres did not significantly improve perceived focus potential. Similarly, Necker Test results were not significantly different when compared with user ratings, confirming that most conditions were similarly suitable for focus. We only observed significant difference between the Library and the City atmospheres. In agreement, perceptual ratings exhibited trends of improvement for focus in the mediated Library. A long term study or a social study could further clarify this effect, whereby the atmosphere functions as a social cue to reduce distractions and noise.

For both restoration and focus, we observed physiological and behavioral changes. HRV was elevated and participants paid more attention to the projected image, as indicated by the Prob. > 1 metric. In contrast, participants looked downwards more often and exhibited less facial expression in focusing conditions. This

¹Due to an error we lost the Necker Test results from two participants.

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study was designed to test acute effects of the atmospheres that occur within minutes. In the future, we plan to investigate longer term effects, which better represent real use case scenarios.

High variance in the perceptual ratings suggests strong personal bias. A user's preference of ambiance depended on both the context and the individual. These results indicate the importance of personal preference modeling. While the City scene was restorative for some participants, they caused the opposite reaction for others. Participants' subjective ratings and physiological responses were in agreement. This supports that it should be possible to use user ratings as an initial system configuration and rely on physiological monitoring in the background to further improve labeling of the atmospheric scenes in recommendation applications. We identified three physiological features that correspond to user's ratings: HRV, Head Orientation, and Neutral Facial Expression. We will use these features in the future to build personal response models. We plan to include a personal response model for each atmospheric scene as metadata in a personalized scene library. Using these models we will be able to experiment with recommendation applications and learn how user-preference and response might change over time.

6.2 Comparison of Signal Processing Approaches

As discussed in Section 4.7 we must define an appropriate metric from the physiological signals that compactly describes the main effects of Mediated Atmospheres and is robust against physiological changes introduced by the user's activity. During the experiment participants performed a series of tasks, which introduced significant changes in their physiological recordings. Despite the activity-dependent fluctuations both metrics based on aggregated mean and probability density estimation correlated with the participant's ratings of the scenes. The results of the two methods were overall in agreement. This indicates the mean score is sufficient to approximate physiological changes in HRV and Facial Expression for similar tasks. However, the probabilistic metric detected nuanced differences in head orientation, which were less pronounced in the comparison of means.

The reason is that the estimated probability density functions describe multiple trends that occurred during the different tasks. For example, the signal illustrated in Figure 8-(2) shows two peaks in HRV, which indicates two main physiological states. In Figure 8-(6) the distribution is plotted for measurements during the break and the reading activity separately. Here we can see that one physiological state was more pronounced during the reading and the other during the break activity.

For Head Orientation, in a simplified scheme, there were three dominant head positions: dropped head, lifted head and distinctly lifted head. By applying the appropriate threshold, it is possible to separate between these states. In the study, we observed significant changes in restorative environments only for distinctly lifted head. Therefore, as we expand the range of possible activities in the office, we expect the probabilistic method, which can identify multiple states, to be more powerful than using mean value alone.

The chest-worn wearable sensor reliably measured heart rate, respiration and motion. Facial feature tracking was successful for approximately 75% of the cases. Hands occluding the face and moving out of the camera frame were the main causes. A camera with wider angle or using multiple cameras could solve part of the problem. In future work, we wish to explore cognitive load measurement through wearable sensors as an alternative to the Necker Test, for example using EEG sensing [38].

7 CONCLUSION

We introduced Mediated Atmospheres, a concept for an adaptive space that manipulates its ambiance to support work-related activities. We implemented a prototype with sensing capabilities such as heart rate monitoring and facial tracking, as well as multimodal output using projection, programmable lighting and sound. We described the reasoning behind our design choices and tested their effectiveness through an human subject experiment. Using the implemented output capabilities, we recreated elements of existing environments and observed them having significant effect on perceived restoration potential without disturbing the occupant's ability to focus.

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Furthermore, we measured physiological and behavioral changes, which were in agreement with subjective ratings. For example, subjects' HRV were elevated in restorative environments and their visual attention focused more on the work area in the focused environment. We compared different metrics for focus and restoration using aggregated mean and probabilistic modeling. In summary, the mean is easy to compute and sufficient for the comparison of distinct physiological states. However, probability density estimation is able to capture more nuanced differences and promises to be more powerful in distinguishing between a wider variety of states. We identified three physiological features that correspond to user's perception: HRV, Head Orientation, and Neutral Facial Expression. These features could be used in the future to inform metadata for atmospheric scenes. Building on our results, we plan to investigate longer-term effect and real use scenarios, including closed-loop control.

A SUPPLEMENTARY MATERIALS

At the end of each experimental session the study participants were presented with the following survey. The survey was presented through the experiment's website and was filled electronically.

Please answer the following questions:

(1) Recall one of those times when you worked hard on a project that required intense and prolonged intellectual effort. Remember how it felt. You probably reached a point where you could tell that your ability to work effectively had started to decline and that you needed a break. You needed to do something during the break that would restore your ability to work effectively on the project. Put yourself in that mind set now and please rate, how good this setting would be to take a break and restore your ability to work effectively on your project.

(*Not very good*) -2 | -1 | 0 | +1 | +2 (*Very good*)

(2) You have just finished breakfast and have only one thing on your agenda for the day. You have a project that you need to think about. Thinking deeply and thoroughly about this project is your goal. Please rate this setting on how good a place it is to accomplish your goal.

(*Not very good*) -2 | -1 | 0 | +1 | +2 (*Very good*)

(3) How much do you like the setting? This is your own personal degree of liking for the setting, and you do not have to worry about whether you are right or wrong or whether you agree with anybody else.

(*Not very much*) -2 | -1 | 0 | +1 | +2 (*Very much*)

(4) Sometimes even when you are near your office it can still feel like you are far away from everyday thoughts and concerns. How much does this setting provide an escape experience or a feeling of being away?

(Not very much) -2 | -1 | 0 | +1 | +2 (Very much)

(5) Some settings have many interesting things that can draw your attention. How much does this setting easily and effortlessly engage your interest? How much does it fascinate you?

(*Not very much*) -2 | -1 | 0 | +1 | +2 (*Very much*)

(6) Sometimes a setting can feel like a whole world of its own. How much does this setting feel like there is much to explore and discover in many directions?

(*Not very much*) -2 | -1 | 0 | +1 | +2 (*Very much*)

(7) Some settings are confusing, have no organisation and have too much going on. Please rate how chaotic and distracting this setting feels?

(*Not very much*) -2 | -1 | 0 | +1 | +2 (*Very much*)

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