Mediated Atmosphere Table (MAT): Adaptive Multimodal Media System for Stress Restoration

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***Abstract*—In the open-plan workspace, which has grown to more than 70% of all offices in the United States, openness and flexibility came at the cost of personal environmental control. Recent evidence has shown a decrease in worker satisfaction due to the lack of privacy and increased noise level and distraction. In this article, we present a vision for using context-aware multimodal augmentation to improve productivity and well-being in the open-plan office. We introduce the mediated atmosphere table (MAT)—a workstation combined with a network of custom environmental control devices (lighting, audio, video, airflow, heating, and scent) to alter the user's local environment and to improve the restorative quality of the user's personal space in the open-plan office. A preliminary user study ($N = 38$) examined the effect on stress development based on subjective measures of perception, as well as objective measures extracted from recordings of heart rate variability. Our findings show that MAT significantly ($p < 0.05$) affects occupants' perception, as well as their physiological response in an open-plan research workspace. Furthermore, we found a significant difference between experimental conditions with and without scent. We provide an exploratory look at the effect of scent and the applications of MAT.**

***Index Terms*—eHealth and mHealth, mobile and ubiquitous systems, multimodal sensors, real-time systems, smart environment, testbed and trials, user experience.**

I. Introduction

OPEN-PLAN workspaces make up more than 70% of all workspaces in the United States [1]. This type of layout provides a more flexible seating arrangement for a higher number of employees at a lower cost and encourages serendipitous interaction between coworkers. However, recent surveys are showing an increase in work-related stress in open-plan offices [2]. Researchers have found that removing boundaries negatively affected workers' cognition, job satisfaction, behavior, and well-being [3], [4].

In the open-plan workspace, openness and flexibility came at the cost of personal environmental control. In an office environment, factors, such as indoor thermal comfort [5]–[7], lighting [8], [9], noise [10]–[12], view [13], and colors [14], [15], have been found to have a substantial influence on workers' cognition and well-being. The theoretical model of workspace stress, defined as the stress provoked by factors of the physical work environment, states that stressors and discomfort, such as noise, temperature, and lighting, can drain workers' energy that could otherwise be used for doing productive work [16]. By enabling workers with control over their environments, we could alleviate conditions that cause them discomfort and thus help reduce workspace stressors and improve mental health [16], [17]. Moreover, we can enhance the worker's productivity and well-being by fine-tuning the ambient conditions to support their activities [14].

We see several opportunities to enhance the user's work experience by matching the environment to the task being performed. For instance, numerous research has shown that by increasing ambient noise level and adding visual complexity and clutter can benefit creative performance and abstract thinking [14], [15], [18]. On the other hand, for focus activity, a high light intensity level and cold color temperature lighting have shown to enhance alertness and improve performance [15], [19]. For learning activity, it has been shown that matching the learning and recall environment will make recall easier [20]. For stress management, certain environmental characteristics have been shown to accelerate stress recovery [14], [21].

Different than the prior work that has shown the use of audiovisual interventions, we leverage a multimodal IoT network for augmentation, which also addresses the user's non-image-forming visual function and sense of smell, temperature, and airflow to reduce the demand on the user's audiovisual bandwidth.

Our design is a *calm* technology that does not distract the user from their primary task by interacting with the user on the periphery of their attention. The foreground (center)/background (periphery) model in human–computer interaction classifies systems according to their demand on the human attentive capacity [22]. For example, reading is a foreground task because it requires focus. On the other hand, sensing the temperature of a place is a background task because it is easy to focus on something else (in the foreground) while still noticing temperature changes.

Given the potent impact of scent on the human mind and emotions, we are interested in exploring its role in the office. Anatomically, the olfactory system is the only sensory system that has a connection to the brain regions that directly process emotions and memories [23]. This makes smell one of the most powerful senses we possess for influencing recall and memory formation [24], cognitive performance [25], and relaxation [26]–[28]. Our approach is

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Fig. 1. Rendering of an open-plan office concept with MATs.

to match the scent to the virtual environment to increase immersion.

In this article, we introduce a vision and implementation of a novel building control system (see Fig. 1) that uses multimodal augmentation to improve productivity and well-being in the open-plan office. We built an IoT system called mediated atmospheres table (MAT) that gives the user control over their local environment (lighting, sound, visual, temperature, and scent) in a shared space. The MAT system is equipped with a set of sensors for the assessment of the user's physiological state. It senses the user's response in real time to evaluate the effect of the environmental intervention and to provide data needed for delivering a personalized experience. We conducted a preliminary study to evaluate the ability of our system for inducing stress recovery in the open-plan work environment.

A. Research Strategy

By combining the multimodal experience with a modular desk system—an integral part of the open-plan work environment—the MAT prototype enables personal control of the user's local surroundings and supports the openness and mobility required for today's agile workspace design. Using the aforementioned multimedia capabilities, MAT can recreate the sensation of a real-world scene, such as a cozy living room or a rejuvenating forest.

Our prototype combines the benefits of an open-plan office and individual workspace together. We envision multiple applications for our MAT prototype, for instance, in an open-plan setting, we can also create neighborhoods, where a group of people who are working together could synchronize their MATs to create a digitally themed team space. Another application is improving customization of hot desking (temporary desk assignment) in an open-plan office by using secure authentication protocols for storing personal preferences and settings in the MAT system. These applications can enable a higher level of personalization by simulating each individual worker's memorable spaces into the open-plan office. For example, the user could record an inspiring environment and reproduce it on the MAT.

As a first step toward these applications, we evaluated MAT's ability to influence the user's stress development in the open-plan workspace through a preliminary experiment. This proof-of-concept experiment provides insights about the effect on perceived restoration and physiological response of the multimodal intervention in comparison to a neutral (typical open-plan office) control condition. Our vision is that we will use all available modalities to create an intelligent space, in other words, we want to understand the effect of the environment as a whole and how it affects users' perceived restoration and physiological response. Therefore, our emphasis was not in studying the individual effects of audio, visual, lighting, etc. However, due to the lack of understanding and novelty of the scent factor, we created a condition in our experiment to study the effect of scent by comparing it with conditions without scent.

In related research, Zhao *et al.* [29], [30] investigated the impact of different themed scenes as the experimental conditions. In this article, we focus on the stress management application in the open-plan workspace using a single forest condition, which was selected based on previous findings. The study was motivated by two hypotheses: 1) the multimodal augmentation without scent (forest atmosphere condition) has a significant effect on the user's perceived restorative quality of the space and physiological response in an open-plan workspace in comparison to the neutral condition and 2) the olfactory augmentation (forest with scent condition) will have a significant effect on the perceived restorative quality of the space and physiological response in comparison to the neural and without-scent condition.

B. Overview

The key contributions of this article are as follows.

1) We present MAT, a multimodal media table that senses the user's physiological state and allows them to personalize and enhance the restorative quality of their local work environment in an open-plan workspace.
2) We evaluate the effects of the prototype system on participant's physiological stress development and perceived restorative quality of the space to test the feasibility of influencing stress recovery in an open-plan environment through multimodal media augmentation.
3) We introduce, measure, and discuss the effect of artificial micro dose scent delivery in the smart building context.

The remainder of this article has four major sections. Section II summarizes the related work that guided this research. The MAT prototype is presented in detail in Section III. The experimentation details and metrics for data analysis are described in Section IV. Finally, Section V provides a discussion and Section VI draws a conclusion to this research.

II. Related Work

To date, numerous studies have investigated ubiquitous computing systems for improving building control or enabling energy saving through optimization by analyzing the user's patterns. Some examples of prior work that focused on adapting to occupant's needs and receiving occupants' feedback are through voting [31], context-awareness [32], gestural control [33], user comfort modeling [34], and sensor networks [35]. Other research introduced new solutions and devices for the control of one's personal space, such as personal temperature control [36]. However, the open-plan office still presents a challenge for providing a comfortable workspace that matches the needs of all its occupants. Through the implementation of a multimodal media digital experience, opportunities to enhance the user's control and immersion could be explored for solving this issue in an open-plan office environment.

Environmental psychologists have extensively shown that natural environments or virtual representations of such could yield restorative and mental healing effects. One applied example is Shinrin-yoku, which means "forest bathing." It involves the process of immersing oneself in a forest environment by using all five senses. Previous research not only showed a significant effect of the Shinrin-yoku approach on the physiological response, such as reducing blood pressure and heart rate, but it also showed the potential for reducing the symptoms for anxiety, depression, and anger [37].

Previous work has found that simulated environments have the potential to yield a higher and faster restoration effect on users. In those studies, the researchers used video and sound clips of nature and urban environments played from a computer [21], as well as physical photographs and slides of restorative and nonrestorative environments [38], [39]. Although these audiovisual digital augmentation appear to yield a restorative effect, it is not an immersive experience. The sense of presence could be achieved by stimulating all of our senses. Dinh *et al.* [40] conducted a study with 322 subjects to research the effect of tactile, olfactory, audio, and visual sensory cues on the subject's memory retention and sense of presence in a virtual environment. They found that the addition of different sensory modalities increased the subject's sense of presence and memory. In another study, de Kort *et al.* [41] found that a bigger screen size provides a higher immersive experience, and thus enhances the restorative effect of the simulated natural environment.

One of the senses that has been underexplored for digital experiences is the sense of smell. Throughout history, aromatherapy has been demonstrated to affect our psychophysiological response, leading to deep relaxation through the use of different odors and has shown potential for reducing chronic pain [42]. Cardamom aromatherapy exhibited the potential for reducing stress and promoting well-being in students [43]. Peppermint smell was used to increase attention and help participants stay focused during task performance [25]. Thyme and rosemary have similar invigorating effects, but the smell of sweet vanilla, lavender, basil, cinnamon, and citrus can be used for inducing relaxation [26]–[28].

Recent advancement of scent technology came along with the discussion of novel applications for personal and wearable scent devices, for instance, a wearable olfactory display that amplifies mobile notifications [44] and an olfactory interface for virtual reality experiences to promote relaxation [45].

The idea of a multimodal media environment in the office that adapts to the user's physiological state was first introduced by Zhao *et al.* [29]. The experiment of this work was performed in a one-person, enclosed office that already provides the user with a great deal of control. Shared environments, such as open-plan spaces and hot desking offices, would benefit the most from this system. The challenge is to create an immersive experience despite the openness implicit in large office spaces and to allow the user to choose to either connect or isolate from the large open office depending on his or her needs. Our examination advances this body of research by introducing a method for real-time sensing of the user's response to multimodal control, and by presenting a prototype for stress management in the open-plan office.

III. Mediated Atmosphere Table Prototype

The MAT is a multimodal media system that interacts with the user's visual, auditory, tactile, and olfactory senses to create an immersive experience (see Fig. 2). It is equipped with a custom LED display, programmable high-intensity color-tunable light fixtures, air circulation, heating, sound, and a scent activation system. In Fig. 3, the data diagram shows how the hardware and software connect to each other. Data is collected from the wearable sensors, cameras, and thermal cameras using the sensor collection server. Based on that data, the scene control server can select a scene from the Scene Library and sends commands to change the lighting network settings, play corresponding environment audio, display a scenery on the screen, and dispense scent matching the selected scene.

A. Display and Sound

The LED display uses a nontypical aspect ratio, a wide format (60 by 26 inch), and a low-resolution diffused display (576 by 256 pixels) to create an ambient and immersive view. The low-resolution image is designed to create *soft fascination*, which does not demand the user's full attention and rather disappears into the background. The size of the LED display is inspired by guidelines developed in previous research [29], which found that the nontypical aspect ratio allows the user to disassociate this type of image presentation from conventional television and that a wide frame-less display enhances the visual immersion. We used a white translucent light diffuser in front of the LED display, which appears as a wall divider when turned off (see Fig. 4). The diffuser eliminates LED hot spots and constrains the viewing angle (half angle[1] $< 15^\circ$). The narrow viewing angle aims to limit the experience to only the person sitting at the desk.

[1]The angle having half the light intensity of a collimated beam shone through a sample perpendicular to the light source.

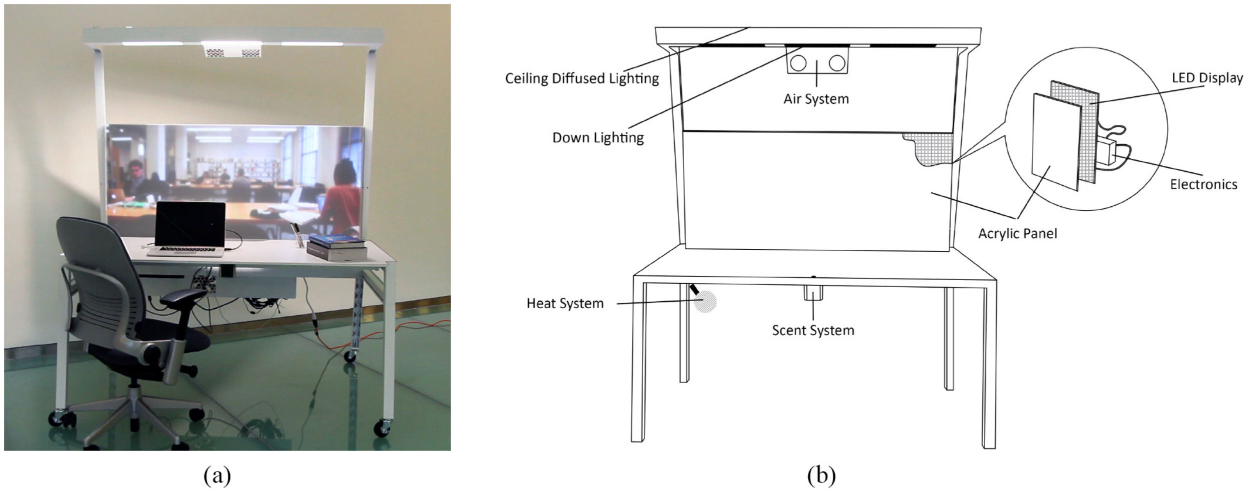

Fig. 2. Illustration of the MAT. (a) Library setting. (b) Systems components.

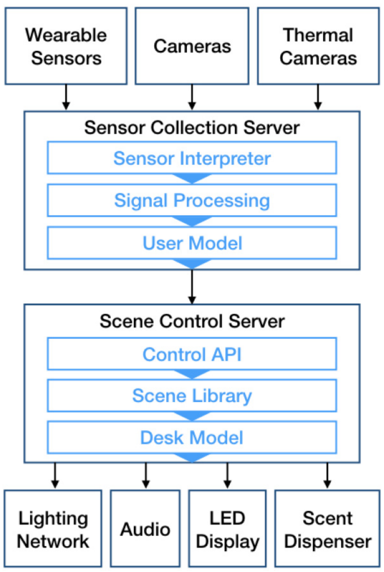

Fig. 3. Software components and data flow diagram.

Fig. 4. Close-up view showing the atmospheric conditions used in the experiment: (a) scenes *forest with scent* and *forest without scent*, which are visually the same and (b) *neutral* scene.

In the experiment described in this article, a pair of commercial noise-canceling headphones, the Bose QuietComfort, is used to deliver ambient sound.

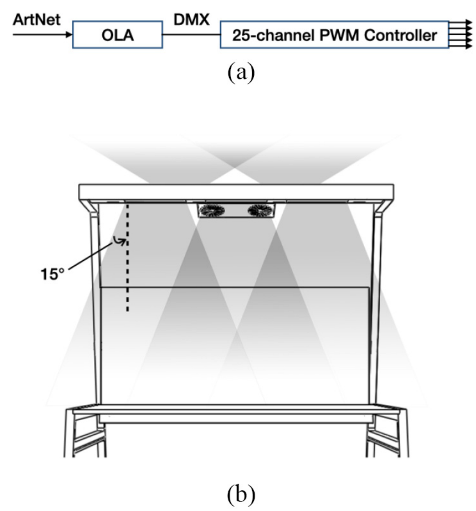

Fig. 5. (a) Lighting control components and protocols. (b) Lighting spread lens configuration.

B. Lighting

The lighting system has five controllable sections with direct (down-lighting) and indirect lighting (diffused ceiling lighting), which allows us to change the directional and diffused quality of the light. The ceiling light creates soft, diffused illumination that enhances the presentation of the surrounding environment. Direct down-lighting, on the other hand, separates the desk from its surroundings by directing the user's attention toward the desk surface.

The lighting control system consists of a open lighting architecture (OLA) backend installed on a Raspberry Pi, which functions as an Ethernet to DMX gateway. It receives control commands from the Scene Control Server using ArtNet—a lighting control protocol designed to transmit DMX512 lighting data over an Ethernet network (see Fig. 5). It uses a simple UDP-based packet structure to provide low overhead data flow [46]. The OLA gateway outputs a DMX512 control signal to a serial interface, which is connected to a 25-channel, 16-bit pulse-width modulation (PWM) lighting controller. Each light section has three colored channels (RGB) and two tunable white channels (2700, 6500K). The maximum output of the colored RGB LEDs per fixture is 790 lumens (lm) with an efficacy of 25–26 lm per watt and the white LEDs are 1022 lm per fixture with an efficacy of 118 lm per watt.

We installed 30° × 30° spread lenses for the down-lights to control the lighting spread, prevent glare, and optimize color mixing between the different colored channels and individual LED hotspots on the table surface. The spread lenses form an optical filter with beam sculpting structures engineered inside a plastic material. The beam angle describes the vertical and horizontal angles of the light cone created by a point source. We selected a narrow 30° beam angle to minimize light leakage to any neighboring desks, while enabling an even light distribution at the desk surface level (see Fig. 5). Our modular system allows us to change the spread lens easily for experimentation.

C. Air Flow and Temperature

An air circulation system mounted on the top of the table pointing toward the user's head and table surface is designed to simulate the sensation of air movement (e.g., light wind in outdoor spaces) and to provide cooling. It consists of two PWM-controlled fans with an adjustable angle. An infrared heating system underneath the table allows for additional temperature control.

Personal comfort control through local cooling and heating systems in the immediate proximity of the user has been shown to improve comfort in shared spaces while also significantly reducing overall energy consumption [47] by widening the range of acceptable room thermostat set points. The position of the air system above the desk pointing toward the user has several benefits. Local circulation in the breathing area improves office workers' perception of air quality [48]. Furthermore, cooling of the hands and head effectively alters the user's temperature sensation [48]. The air velocity at the user's head position is less than 1 m/s to ensure comfort.

For the heating system, we experimented with various heating methods, e.g., conduction and radiation. We selected a 175-W quartz infrared light for its immediate response time. The infrared lights are installed underneath the desk since the most desirable personal heating locations are the legs and feet [47]: in particular, feet are the most common area of discomfort complaints [49].

The controller for the air flow system consists of an AVR microcontroller platform with an Ethernet control chip (Wiznet W5100). The Scene Control Server sends TCP packages to the device to set the airflow levels of the PWM-controlled fans with 8-bit resolution. For the infrared heater, we used a commercial wireless dimmer with a RESTful API.

D. Scent

The prototype uses the Aroma Shooter from aromajoin [50] to display scent. It is installed under the desk surface with an opening for the scent to spray toward the user. The Aroma Shooter uses a solid (no fluids) scent cartridge and creates micro-dose scent bursts that dissipate within minutes.

We worked closely with industry experts to identify and configure the optimal scent system for our office application. A major challenge of applying scent is the duration of each release and reach of the stimulus. In an open-plan office setting, an unwanted, lingering mixture of scents would outweigh any potential benefits of the scent display.

We experimented with two setups. First, we used ultrasonic misters, which were installed behind the fans above the desk. Through a custom PCB board [51] we were able to activate the mister and fans from the Scene Control Server. The airflow carried the scent to the user's breathing area.

In the final installation, we used the Aroma Shooter, which uses a dry medium and an air burst to deliver a small dose of scent to a precise location. It was more suitable for the open-plan office application because of its high temporal and spatial control resolution. Fluids, such as oils and mists, form droplets that can attach to surrounding surfaces, which make them difficult to control and can linger in the space. The Aroma Shooter delivers the scent to the breathing area through a perforated opening of 1 cm diameter on the table surface. Only the user seated at the desk can perceive the scent. This should help to limit the scent from affecting adjacent MATs in an open-plan layout.

The Aroma Shooter can toggle between scents with 100-millisecond (ms) temporal resolution. For the scenes, we typically used 10–20 bursts of 100-ms duration with 1-s interval at the beginning of each scene (after scene transition). Afterward, we turned off the device to avoid over stimulating and saturating the user's senses. Additional bursts to reactivate the scent are possible. For each scene, we selected a scent that matched best to the content of the video. The Aroma Shooter contains six cartridges, and each can carry a different scent. An additional advantage of the dry carrier medium is the small volume required, which enables a compact form factor.

E. Scene Control Server

The Scene Control Server (see Fig. 3) interprets incoming commands using the Control API to control each media component. A desk model calibrates the control commands according to the configuration and physical location of the actuators. Finally, the scene library contains media files and preset control settings.

We created over 30 atmospheric scenes representing different physical locations, for example, a tropical beach, a library, or a Christmas living room with a cozy fireplace. In the scene library, each scene is described as a collection of settings. The settings include audio and video media, airflow pattern, lighting position and color, sound level, scent type, and scent release duration.

We created a room model that would convert the scene settings to the hardware setup. The room model abstraction allows us to experiment with different output devices and physical configurations. For example, if one would modify the position of the lighting fixtures or the location of the scent dispenser, then the desk model is updated to fine-tune lighting and scent intensity settings in order to accommodate these changes.

We introduced the concept of virtual light sources as a tool to configure and calculate lighting settings. Virtual light sources can be placed anywhere in the proximity of the desk. The location of the virtual light source is either an approximation of light measurements performed during video recording of the scene or the result of a light analysis of the video footage if no measurements were available. Virtual light sources approximate the position of any lights, such as ceiling lights, windows, or the sun in the scenes. We then define the channel brightness settings of the physical light (c) as a function of the distances (d_i) to the virtual light sources and the color, brightness ($\hat{c}_i$), and size settings (s_i)

$$c = \sum_i \hat{c}_i * e^{-d_i/s_i}. \quad (1)$$

During a scene transition, we crossfade between the lighting settings of the current and the new scene. All other settings fade out to an off-state and then fade back into the new scene setting. In particular, the blank white screen during the transition creates a sense of separation between the current and the new ambiance.

F. Sensors

The prototype is equipped with a local network of sensors to monitor the user's physiological state (see Fig. 3). Sensors include wearable health monitors, visible light cameras, and infrared thermal cameras. In the experiment described in this article, we evaluated the user's physiological response using the Zephyr Bioharness 3 health monitor chest strap for electrocardiogram (ECG) measurements (for details see Section IV-A4).

1) Heart Rate Variability: One of the most efficient and noninvasive objective measures of the autonomic nervous system (ANS) is the heart rate variability (HRV) [52], the variation in time intervals between subsequent heartbeats. This metric has been used extensively by environmental psychologists to assess the influence of nature on stress recovery. For example, Hjortskov *et al.* [53] found that HRV reacts faster and more sensitively to mental stress, such as computer work. In addition, a review correlating sympathetic and parasympathetic activity with job stress and burnout found that high stress is associated with an increased heart rate and decrease in HRV [54].

A variety of time-domain measures of HRV could be used: 1) standard deviation of beat-to-beat intervals (SDNN) and 2) HRV triangular index are both used to estimate the overall HRV; 3) standard deviation of the average beat-to-beat intervals (SDANN), used to estimate long-term components of HRV; and 4) root-mean square of successive differences (RMSSDs), used to estimate short-term components of HRV. For recordings of short durations, SDNN and RMSSD methods could be used. However, for assessing overall HRV, SDNN is preferred. The time window affects the analysis of the recording, thus it is important that all the analyses use the same window length for comparison.

2) Facial Features and Temperature: Facial expressions are indicative of a user's emotion and attention. We equipped the prototype with two visible light cameras to track the user's facial features from two angles. We are also able to produce a depth map using stereo vision. Additionally, we can use the cameras for face recognition to identify the user and trigger personalized settings.

Facial thermal temperature fluctuation is an indicator of arousal and cognitive load [55]. For example, it has been found that lower nose temperature and higher forehead temperature is correlated to task difficulty. We included a thermal camera in the prototype to further investigate thermal imaging for contact-less measurement of mental state.

G. Sensor Collection Server

We created a custom software called the Sensor Collection Server that manages the connection, streaming, and storing of sensor data. The software, written in Python, is an event-based server, which consists of sensor interpretation, signal processing, and user modeling components. The sensor interpretation component receives and converts the various sensor formats for processing. The signal processing component then computes features such as HRV or face orientation using the raw sensor input. The user model component stores the observations for each user and computes a statistical model, e.g., z-scores and kernel density estimation (KDE).

Our long-term research objective for the MAT prototype is to explore different methods for context-aware control. Therefore, in our software, we can easily inject and alter the inference algorithm that controls scene changes based on physiological response data. We can create different context-aware filters between the Sensor Collection Server and Scene Control Server.

IV. Experiment

A. Method

1) Experimental Design: We followed an experimental design that is typically used in psychology research for evaluating restorative environmental effects. Participants performed a stress-inducing task, followed by a restorative break in the test condition [21], [29]. While performing these tasks, the physiological stress onset and recovery can be observed within 1 m [13]. We recorded participants' responses in three conditions using objective measures (HRV as an indicator of the parasympathetic activation of the autonomous nervous system) and subjective measures (a set of survey questions including the Perceived Restoration Scale).

We used a repeated-measures experiment design with the type of atmosphere condition as a within-subject variable. The three experiment conditions are as follows.

Neutral: This atmosphere condition represents the original open-plan workspace environment without any ambient augmentation. The LED panels display no visuals. The lighting fixtures produce a neutral color temperature (6500 K) and a typical brightness level for an office environment with uniform distribution. There are no auditory nor olfactory augmentations. The fans are disabled.

Forest Without Scent: The LED panels display a video of a forest in colorful autumn color. It shows a view of the pristine water flowing calmly down a shallow mountain river right in the middle of the autumn forest. The soft warm light (3500 K) simulates the afternoon time. One hears the sound of the stream gliding smoothly through the river rocks and birds can be heard chirping in the distance. The light sources located above the table generate a warm light to match the described visuals. The fan system is enabled to simulate a gentle breeze. This condition does not have a scent.

Forest With Scent: Has the same settings as the forest without scent condition, except a forest scent mixture (*Forest Dream created by International Flavors and Fragrances Inc.*) is automatically dispensed to generate an olfactory augmentation. The scent captures the damp ground of the forest, where the earthy note is most emphasized. It could be described as green, mossy, and woody. It contains oakmoss (moss fern-like odor), patchouli (earthy), and labdanum (dark woody).

2) Participants and Protocol: For the preliminary experiment, a convenience sample was used consisting of 38 noncompensated participants (35% females and 65% males) from the university's extended community. Our target group was office workers who are familiar with open office workspaces, which include graduate students, post-docs, research affiliates, and administrators. The average age was 28 years old ($M = 27.7, SD = 11.1$).

The experiment was conducted in an open-plan research workspace during the typically busy hours of the workday. Office workers who are not actively participating in the experiment were free to walk around and interact with others per usual during the experiment. MAT was placed in a high foot-traffic section of the open-plan research workspace, located in front of a conference table, next to an electronic lab space and behind other graduate assistants' desks as shown in Fig. 6.

Participants began the study with a tutorial of an example session and several cognitive tasks (approx. 20 min). A website presented instructions, while the system collected physiological data. Afterward, participants experienced the same experiment session three times (approx. 45 min). A different condition was chosen in randomized order for each session. A session consisted of 1) 30 s of neutral condition to disengage from previous experience; 2) 30 s of familiarization with test condition; 3) 3 min of reading comprehension task similar to those given at a graduate-level standardized test; 4) 3 min of break (in the Forest with Scent condition, scent bursts were released at the beginning of this segment); and 5) unlimited time for the in-experiment survey. After all three sessions, the participant filled out the post-study survey and was then briefed on the scent factor (approx. 5 min). Participants were instructed to wear the headphones and the sensor during the entirety of the experiment.

3) Subjective Measures: We collected participants' responses through the in-experiment survey (direct rating using a five-point Likert scale) completed at the end of each session (conditions). We used metrics inspired by related literature [29]. Two questions present the user with a scenario to assess whether the environment is suitable for focus and restoration tasks. Another five questions consist of the Perceived Restoration Scale. Two additional questions ask about the familiarity and intensity of the condition. We implemented Friedman's test to compare the total rating, and

Fig. 6. This floor plan shows the open-plan research workspace. The prototype table is annotated as MAT. Within this area, there are no enclosed spaces, and people interact frequently with each other, including meetings, discussions, and presentations. 48" tall, see-through shelves are positioned between some desks. The distance between MAT and desk 1 is approx. 5 ft.

the Wilcoxon signed-rank test for *post-hoc* comparison. The dependent variable was the total rating from the five-point Likert scale.

Before the experiment, we informed the participants that during the experiment some conditions might appear similar but did not disclose the scent factor. In the post-study survey, we asked participants whether they noticed any scent, and to rate the intensity, familiarity, and preference of the scent experience on a five-point Likert scale.

4) Objective Measures: We used three HRV measures:

1) mean HRV;
2) probability of observing HRV higher than the participant's average (Prob. > 0);
3) probability of observing HRV more than one standard deviation higher than participant's average (Prob. > 1).

In addition to the statistical mean HRV, we also computed a probabilistic model that takes into account unique features of the statistical distribution of the user's HRV. To compute the probability metric, we constructed a probability density function (pdf) : $p(x)$—an estimation of the probability to observe the physiological state x—based on the recorded HRV data and using KDE with a Gaussian Kernel as described in [29].

For comparison between conditions, we implemented a one-way analysis of variance (ANOVA), followed by t-tests for

TABLE I
MEAN AND STANDARD DEVIATION OF THE TOTAL RATING OF THE PERCEIVED RESTORATION AND FOCUS

	Perceived Restoration and Focus		
	Neutral	Forest w. Scent	Forest w/o Scent
M	-0.21	0.89	0.94
SD	0.59	0.48	0.48

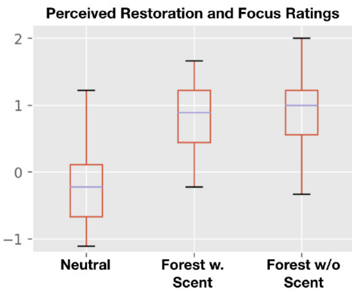

Fig. 7. Box plots of the effects on perception—participants' ratings on perceived restoration and focus.

comparing the significance between the pairs. We only considered the measurements during the stress-inducing (reading) task and the stress-recovery (break). In a follow-up analysis for evaluating the effect of the intervention when the primary task is reading, we compared only data recorded during the stress-inducing activity.

The health monitor [56] transmitted the real-time data interbeat R–R intervals, generated from ECG signals sampled at 1000 Hz, via Bluetooth to the Sensor Collection Server. Eleven datasets were disregarded because of connectivity failure. For the remaining datasets, we removed outliers that were outside a 200-ms band around the rolling mean of the raw data (window size of 100 at 18-Hz sampling rate). R–R data was resampled using linear interpolation to equidistant samples at 18 Hz. We applied a rolling standard deviation (SDNN) with a window size of 1000 data points to the resampled R–R data. The result was normalized (z-score) for each participant and smoothed using a moving average filter with a window of 180 data points.

B. Experimental Results

1) Effects on Perception: Friedman's test has shown significant ($p < 0.05$) difference in perception among the three atmosphere conditions ($\chi^2(36) = 39.78, p = 0.000$) (see Table I). Post-hoc comparisons, using a Wilcoxon signed-rank test, confirmed that both *Forest with scent* ($Z = 17.50, p = 0.000$) and *Forest without scent* ($Z = 13.0, p = 0.000$) were significantly ($p < 0.05$) better perceived than the *Neutral* condition. There were no significant differences between *Forest with scent* and *Forest without scent* ($Z = 194.50, p = 0.294$). Two subjects were removed due to incomplete answers in the survey. Fig. 7 shows the generated box plots of the results from the participants' perceived restoration and focus ratings on each condition.

26 of the 38 participants reported that they noticed the scent in the post study survey. Participants' ratings of the scent's intensity, familiarity, and whether they liked the scent experience (preference) are summarized in Table II. Overall,

TABLE II
MEAN AND STANDARD DEVIATION OF PARTICIPANTS' PERCEPTION OF THE SCENT EXPERIENCE

	Perception of the scent experience		
	Intensity	Familiarity	Preference
M	-0.26	0.09	0.50
SD	1.29	1.19	1.08

TABLE III
SESSION MEAN AND STANDARD DEVIATION OF HRV METRICS FOR THE THREE EXPERIMENTAL CONDITIONS

HRV Metrics Mean and Standard Deviation				
Metric		*Neutral*	*Forest w. scent*	*Forest w/o scent*
Mean	M	-0.083	-0.057	0.155
	SD	0.225	0.436	0.409
$Prob > 0$	M	0.395	0.399	0.497
	SD	0.094	0.206	0.167
$Prob > 1$	M	0.130	0.132	0.199
	SD	0.068	0.120	0.139

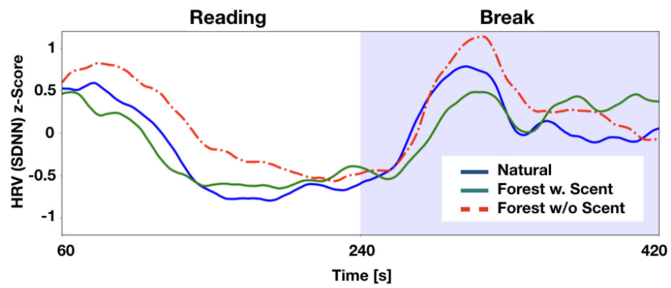

Fig. 8. HRV (SDNN) z-score during *reading* and *break* activities for three conditions, averaged over all study participants.

participants found the intensity weak, were neutral about the familiarity, but liked the scent experience.

2) Effects on Physiology: We found significant ($p < 0.05$) difference in HRV among the three conditions for all three HRV metrics (Mean: $F(2, 52) = 3.767, p = 0.030$; Prob. > 0: $F(2, 52) = 3.779$, $p = 0.029$; Prob. > 1: $F(2, 52) = 3.292$, $p = 0.045$) during the stress-inducing and recovery tasks. Mean and standard deviation are detailed in Table III. Post-hoc analysis showed that HRV in the Forest without scent condition was significantly higher than the Neutral condition for all three HRV metrics (Mean: $t(27) = -2.98, p = 0.006$; Prob. > 0: $t(27) = -3.36$, $p = 0.002$; Prob. > 1: $t(27) = -2.33$, $p = 0.028$).

Surprisingly, there was no significant improvement in the Forest with scent condition in comparison to the Neutral condition. Furthermore, HRV in the Forest without scent condition was significantly higher than scented condition for two of the three metrics (Mean: $t(27) = -2.08, p = 0.048$; *Prob.* > 0: $t(27) = -2.09, p = 0.047$).

Fig. 8 shows the HRV time-series signal averaged over all participants. HRV decreased during the stress-inducing reading task and recovers during the break activity. Overall, stress development was slower and recovery was higher in the Forest condition without scent compared to the other conditions.

A significant ($p < 0.05$) difference in HRV was present during the stress inducting task in all three HRV metrics

TABLE IV
READING-PERIOD ONLY MEAN AND STANDARD DEVIATION OF HRV METRICS FOR THE THREE EXPERIMENTAL CONDITIONS

Reading-period Only HRV Metrics M and SD

Metric		*Neutral*	*Forest w. scent*	*Forest w/o scent*
Mean	M	-0.310	-0.321	0.0111
	SD	0.299	0.409	0.526
$Prob > 0$	M	0.279	0.285	0.435
	SD	0.134	0.208	0.220
$Prob > 1$	M	0.077	0.053	0.178
	SD	0.105	0.091	0.160

(Mean: $F(2, 52) = 6.401, p = 0.003$; Prob. > 0: $F(2, 52) = 6.240, p = 0.004$; Prob. > 1: $F(2, 52) = 8.781, p = 0.001$). Mean and standard deviation are detailed in Table IV. Post-hoc analysis show that all three HRV metrics were significantly higher in the Forest without scent condition compared to the other two conditions.

V. DISCUSSION

Our results agree with our first hypothesis, that the forest atmosphere condition without scent has a significant effect on the user's perceived restorative quality of the workspace and their physiological response to a stress-inducing and stress-recovery task in comparison to the neutral condition. This outcome confirms the potential of MAT for improving well-being in an open-plan workspace.

Furthermore, we observed a preferred HRV state during the reading task period, which suggests that the environment had an impact on the user while their primary task was reading. This outcome supports our peripheral approach to deliver the benefit of the optimized environment by interacting in the background of the user's attention.

MAT is the first demonstration of a portable, multimodal, control-embedded workspace that could be used to complement the benefits of the open-plan work environment. Our preliminary results in an open-plan office indicate that our design was successful in creating a restorative experience without the boundaries of an enclosed space.

Despite our intuition that adding a matching scent to the forest scene would increase restorative effect closer to the Shinrin-yoku method, our data did not agree. There was no significant difference in participants' HRV metrics between the forest with scent and the neutral conditions. Since our approach is only one way to stimulate the sense of smell, we cannot conclude with certainty that other strategies are ineffective too. We can only conclude that ours were not intense, appropriate, or adequate enough to induce an effect in stress recovery compared to the other conditions.

68% of all participants noticed the scent and overall reported that they liked the scent experience. However, in the scented condition, we recorded the largest variance in the user's physiological response, which is an indication that the scent experience in the preliminary study was rather dependent on individuals.

Participants indicated that they perceived the scented and unscented forest conditions to be very similar and significantly different from the neutral condition. Although the participants did not expect nor report a difference between the two forest conditions, we measured a significant difference in their HRV. This observation establishes an important design consideration for scent augmentation in the work environment. The effect of scent stimuli used here looks to be rather subliminal to the user compared to the visual/audio effect of the unscented environment. We believe that it is important for users to be aware of the impact of the environment on them to better control the stressors. Therefore, in future studies, it will be beneficial to isolate each individual sensory modality built on the MAT and analyze how each of them affects the user's mental state compared to the system as a whole. At the same time, it is important to examine the combined effect, because research on multimodal environmental control is lacking in current research literature [57]. These studies will enable the development of a closed-loop system for the open-plan office that recommends personalized settings based on the user's individual physiological response.

The proof-of-concept experiment introduced in this article focused on the acute effect on the user's stress development during and after a stressful task. Stress development is observable within seconds and gives insight into the person's ability to recover from stress in the given environment [13]. This preliminary experiment functions as an approximation to real world high-stress situations, such as performing a reading comprehension task under time pressure. However, a longitudinal study is necessary to understand the long-term effects. Focus work is the most important work mode for knowledge workers. It accounts for 54% of the average work week, and the time spent focusing at the workplace has been continuously increasing [58]. While our study is limited to the focus work mode, its results have an impact on the most relevant area for improving productivity and wellbeing in the modern open-plan workspace. A significant portion of each open-plan space should be dedicated for focus work to meet the employees' growing needs. Our results suggest replacing ordinary workstations with MATs in the focus area could significantly improve physiological and perceptual outcome. Recent workplace research has found that employees with choice in their work environment are more effective [58], [59]. Our result confirmed that choice in local environmental control can improve the user's physiological and perceptual response without changing their physical location.

As discussed in the introduction (see Section I), there are many applications for MAT besides stress restoration, for instance, to improve memorization by associative thinking, or to help users stay in focus with just-in-time intervention. Our preliminary results are encouraging for future research on algorithms for intelligent control using MAT systems and on applications for workplace productivity and well-being.

As described in our prototype section (see Section III), we took many aspects of open-plan compatibility into consideration, e.g., display viewing angle, lighting spread, scent micro dosing, and local temperature control. These technical features will enable us to better determine the interference of multiple prototypes next to each other, which is an important aspect of the open-plan use case: more specifically, exploring how different desk arrangements in an open-plan workspace affect the user's mental states. For example, to minimize the interference of neighboring desks, they could be arranged in a hexagonal shape, which places the adjacent desks outside of their screens' viewing angles.

Although our experiment is limited to one table at this moment, we are ultimately interested in moving toward improving multiuser experience using several MATs arranged in a way that could enhance collaboration in an open-plan workspace—e.g., exploring the synchronized neighborhood application and context-aware personalization in an open-plan environment, as mentioned in the introduction.

Furthermore, we can imagine numerous applications with scent using MAT system besides stress restoration, such as ambient notification methods or memory enhancement through scent cues. Using our data collection methods, we could develop a personal scent experience model that learns over time the individual's response to scent molecules over time and recommends an appropriate scent for the user.

In this article, we also introduced a comprehensive selection of background research. We discussed the use of scent and highlighted several discussion points that will be relevant for future research incorporating scent factor, e.g., the potency of scent to alter the experience of the scene, the importance of personalization, and the user's awareness of scent.

VI. Conclusion

In this article, we introduced the MAT, a multimodal augmentation system for indoor simulation of environments to help open-plan office workers enhance their productivity and well-being. Our system takes an IoT view of coordinating lighting, scent, heating/cooling, and audio/video as driven automatically by detected autonomic user response. We evaluated MAT's effectiveness on stress restoration with a study on 38 participants in an open-plan research workspace. Based on the physiological measure and subjective survey ratings, MAT has shown that it is capable of enhancing occupants' stress restoration. The implication of this result means that MAT has the potential to help alleviate at least some of the negative effects of the open-plan workspace. Furthermore, our experiment indicated that scent can significantly alter the user's experience of the work environment without the awareness of the user. We believe this illustrates the need for improving workers' perception of how various factors in their environment can affect them. Despite the fact that the user is largely surrounded (openly) by their primary environment, our system is able to create the illusion and associated mindset of being present in a different environment. Our approach and the design decisions leading up to our findings could inform research in the domain of distance education and immersive telepresence that are seeking to understand, create, or transform the perception of presence in remote spaces.

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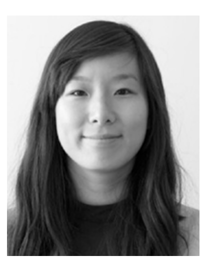

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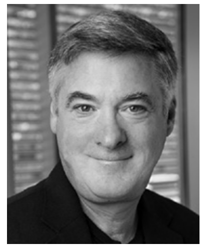

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