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Psychological and physiological responses to stressful situations in immersive virtual reality: Differences between users who practice mindfulness meditation and controls

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Abstract

Several studies in the literature have shown positive psychophysical effects during or immediately after mindfulness meditation. However, the extent to which such positive effects are maintained in real-life, stressful contexts, remains unclear. This paper investigates the effects of an 8-week mindfulness-oriented meditation (MOM) program on the psychological and physiological responses evoked by immersive virtual environments (IVEs) that simulate emergency situations that may occur in life. Before and after the 8-week period, healthy MOM participants and a group of controls not involved in any meditation course were administered self-report measures of mindfulness and anxiety, and acted in the IVEs while a set of physiological parameters were recorded. Responses of MOM participants to the immersive virtual experiences were different from those of controls. MOM participants showed increased mindfulness and decreased anxiety levels. They also showed decreased heart rate and corrugator muscle activity while facing IVEs. We explain these results in terms of the awareness and acceptance components of mindfulness. More generally, the present experimental methods could also open up new lines of research that combine psychological and physiological indices with ecologically valid stimuli provided by IVEs in an effort to increase understanding of the impact of mindfulness meditation on realistic life situations.

Keywords: Virtual reality; Mindfulness meditation; Anxiety; Physiological measures; Heart rate; Muscle activity.

1. Introduction

Rooted in Eastern contemplative traditions, mindfulness meditation (MM) is usually conceptualized as nonjudgmental attention to present moment somatosensory and mental experience (Kabat-Zinn, 1990, 2003; Brown & Ryan, 2003; Lutz, Slagter, Dunne, & Davidson, 2008; Crescentini & Capurso, 2015). Initially formalized for patients with chronic pain (e.g., Kabat-Zinn, 1982; see Baer, 2003, 2010; Didonna, 2009 for discussions of different forms of MM therapies), MM interventions have been shown to be effective for the treatment of different types of physical and psychological problems observed in individuals of various age ranges and in different clinical and non-clinical contexts (for reviews see Didonna, 2009; Brown, Ryan, & Creswell, 2007; Chiesa & Serretti, 2010; Goyal et al., 2014).

For example, a number of studies based on self-report measures documented positive effects of MM therapies on anxiety, stress reactivity, depressive symptoms, ruminative thoughts, mood, and ability to regulate disturbing emotions in patients with anxiety and depressive disorders as well as in healthy individuals (Kabat-Zinn et al., 1992; Evans et al., 2008; Hoge et al., 2013; Hofmann, Sawyer, Witt, & Oh, 2010; Desrosiers, Vine, Klemanski, & Nolen-Hoeksema, 2013; Garland, Gaylord, & Fredrickson, 2011; Chiesa & Serretti, 2010; Jain et al., 2007). In these classes of patients as well as in non-clinical samples, such MM-related positive outcomes on mental health also seem to impact physiological parameters associated with stress and anxiety. For example, it has recently been shown in non-clinical populations that a brief training in mindfulness meditation (3 to 10 days of Vipassana meditation) leads to reduced heart rate (Zeidan, Johnson, Gordon, & Goolkasian, 2010) and increased heart rate variability (which is related to well-being and positive affect; Krygier et al., 2013) immediately after or during meditation tasks. Such findings have been considered to reflect feelings of relaxation (which decreases physiological arousal) or states of effortful, positive immersion in an activity promoted by MM.

Similarly, other longitudinal, within-subject studies or cross-sectional designs in which experienced meditators were compared to naïve meditators or meditation conditions to control conditions (e.g., relaxation or wait-list control conditions), have reported physiological changes during MM. Such changes include reduction of heart and respiratory rates and reduction in skin conductance level, in both clinical (e.g., individuals with fibromyalgia, a chronic pain syndrome; Lush et al., 2009) and non-clinical populations (Cahn & Polich, 2006; Ditto, Eclache, & Goldman, 2006; Delmonte, 1984, 1985; Rubia, 2009). Moreover, a recent study on a sample of depressed patients (Rohde, Adolph, Dietrich, & Michalak, 2014) was able to link negative emotional reactions, experienced when attention drifted during a MM exercise in which subjects had to focus nonjudgmentally on breathing, to electromyographic response of the corrugator supercilii muscle. The activation of this muscle has been shown to be generally associated with negative affect, and the study by Rodhe et al. (2014) observed increased corrugator activity in depressed vs. healthy individuals after drifting from breathing, a finding that can suggest a deficit of depressed patients in the non-judgmental experience component of mindfulness.

Globally, these psychophysiological findings have been interpreted in terms of a wakeful hypometabolic state promoted by MM. This state would be characterized by increased parasympathetic nervous activity (indicative of physiological relaxation and stress relief) and decreased sympathetic activity (e.g., Rubia, 2009). However, one should note that previous studies focused on the health effects of MM therapies have generally monitored physiological parameters immediately after or during MM exercises. This does not shed light about if and how such positive effects of MM translate and generalize to wider, real-world scenarios.

Virtual reality (VR) may represent a more holistic and ecological research instrument, providing users with unique, realistic and immersive experiences that are under full experimenter's control and could open up new possibilities to investigate behavioral and physiological responses of meditators to stressful real-world situations.

In the last years, it has been shown that VR exposure can be so effective in terms of experimental realism as to elicit and modulate psychophysiological symptoms of anxiety and fear reactions (e.g., in terms of electrodermal activity), in both patients with anxiety disorders and healthy individuals (Diemer, Mühlberger, Pauli, & Zwanzger, 2014). More specifically, immersive virtual reality systems, as the one we use in this study, exploit realistic 3D graphics, stereoscopic viewing, and head tracking to create interactive, first-person experiences that can be more ecologically valid than traditional, non-interactive experimental stimuli (written text as well as audio-visual materials; e.g., see Parsons, 2011) and produce users' physiological responses that are consistent with real-world experiences (Parsons et al., 2009; Slater, Usoh, & Steed, 1994, Slater, Khanna, Mortensen, & Yu, 2009; Insko, 2003; Meehan et al., 2005; Chittaro, 2014; Zanon et al., 2014; Patil et al., 2014; Chittaro & Buttussi, 2015). For example, immersive simulations of emergency situations - such as fires, accidents and other life-threatening events - can provide participants with visual and auditory stimuli that are able to induce negative emotions such as anxiety (Chittaro, 2014) and fear (Chittaro & Buttussi, 2015) as a real emergency would do. Moreover, behavioral responses to virtual emergencies are also consistent with real-world ones, even when particular behaviors such as prosocial behavior (Zanon et al., 2014) or ethnic discrimination (Gamberini, Chittaro, Spagnolli, & Carlesso, 2015) are considered.

To date, the potential of VR in MM studies has been scarcely explored. A few studies have recently tried to use VR and immersive systems to foster the adoption of meditative states (Vidyarthi & Riecke, 2014) or self-compassion (an important construct related to MM, see Crescentini & Capurso, 2015) (Falconer et al., 2014). In line with these recent attempts to combine VR and meditation, earlier research explored the use of VR in combination with mindfulness and relaxation in the treatment of patients with physical and psychological problems such as chronic pain (e.g., fibromyalgia) and posttraumatic stress disorder (Spira et al., 2006; Gromala et al., 2011; Botella et al., 2013; see also Tong et al., 2015). However, to the best of our knowledge, no study has employed VR as an instrument to study how meditators respond to stressful situations that simulate, through interactive immersive experiences in controlled conditions, emergencies that occur in real life.

The aim of the current longitudinal research was to investigate the direct impact of a mindfulness-oriented meditation (MOM) intervention on the psychological and physiological responses evoked by four immersive virtual environments (IVEs) that were designed to elicit different levels of stress (low and high, see section on Immersive Virtual Environments) and that simulated real-life scenarios and activities. We studied two groups of healthy adults, one group participating in an 8-week MOM training and the second serving as matched control group whose members were not involved in any meditation intervention. In addition to self-report measures of dispositional mindfulness and trait and state anxiety, we recorded a set of physiological parameters (cardiac, electrodermal, electromyographic, and respiratory activity) while subjects were immersed and acted in the IVEs. This was done in both groups in two different sessions (i.e., before and after the 8-week period during which one of the groups was involved in MOM training). We expected to find evidence of reduced perceived stress and anxiety as well as physiological signs of emotional deactivation and reduced arousal in the MOM subjects when they faced demanding IVEs after vs. before the meditation training.

2. Materials and Methods

2.1. Participants

A total of 41 Italian participants were recruited for the study. Twenty-one participants took part in the MOM training (mean age = 43.33, SD = 10.23; mean years of education: 15.38, SD = 3.52). They were recruited through advertisements and by word of mouth from employees (administrative personnel, nurses and physicians) of the hospital "Santa Maria della Misericordia" in Udine, Italy. To control for possible influence of occupation, age, education level and gender on the measured psychological and physiological variables, control participants were also recruited among the employees of the same hospital: each MOM participant was asked to recruit in the study a colleague who was potentially interested in participating in a future MOM course. The control group consisted of 20 participants who were not involved in any meditation training (mean age = 36.75, SD = 9.85; mean years of education: 15.80, SD = 3.15). Overall, five participants (3 MOM and 2 control participants) were excluded from all the analyses reported below because of technical problems with the physiological recording and/or IVEs described below (2 cases) or because they did not complete the psychological and physiological evaluation (3 cases). Thus, the reported results are based on two groups of 18 individuals. Independent sample t-tests showed that the two groups were matched for age (MOM: M = 42.88, SD = 10.99; Controls: M = 36.94, SD = 10.39; t (34) = 1.66, p = .10), years of education (MOM: M = 15.44, SD = 3.71; Controls: M = 15.55, SD = 3.22; t (34) = .09, p = .92), and gender (3 males and 15 females in each group). Two testing sessions (before and after the MOM training for the MOM group and two temporally matched sessions for the control group) were organized to administer all study participants the experimental tasks and questionnaires described below. The two participant groups were also comparable in terms of days spent between the two testing sessions (MOM: M = 67.72, SD = 7.16; Controls: M = 68.22, SD = 9.01; t (34) = .18, p = .85). In the MOM group, the first testing took place on average 7.33 days before the MOM course start date (range: 0-13 days) while the second testing took place on average 12.38 days (range: 5-29 days) after the MOM course end date.

It must be noted that all recruited participants had no previous experience with mindfulness meditation and with the outcome measures used in the study. All participants reported normal or corrected-to normal vision, and no past history of neurological or mental illness. Signed informed consent was obtained before participation in the study from all participants.

2.2. Mindfulness Oriented Meditation (MOM) training

The MOM course was led by the first and last author of this paper. Both have several years of experience with mindfulness meditation. The training was based on the practice (summarized below) proposed by Fabbro and Muratori (2012), Crescentini et al. (2014), Crescentini, Matiz, and Fabbro (2015), and Campanella, Crescentini, Urgesi, and Fabbro (2014), which are in turn based on the Mindfulness Based Stress Reduction program (Kabat-Zinn, 1982, 1990, 2003). The MOM course consisted of 8 weekly meetings of about two hours each. Each meeting was organized in 3 phases: (a) up to 30 min of active teaching on topics related to meditative practice, (b) 30 min of MOM practice (which was divided into 3 parts of about 10 min each: (i) mindfulness of breathing, (ii) contemplation of bodily phenomena, and (iii) vipassana meditation in which participants tried to non-judgmentally observe their here-and-now mental experience), and (c) a final debriefing of up to one hour during which participants could share their experiences and ask questions to the instructors (see Crescentini et al., 2014, Crescentini, Matiz, & Fabbro, 2015 for further details on the MOM training procedures). At the end of the first meeting, MOM participants were given a

CD with a recording of the voice of the instructor (FF), guiding a MOM practice session of half an hour. Participants were encouraged to listen to the CD as an aid for homework assignments, which consisted of 30 min of daily meditation practice, and were required to keep a written daily diary of the times and duration of the practice.

2.3. Questionnaires and IVE tasks

2.3.1. Questionnaires

To measure possible changes in dispositional mindfulness due to participation in the MOM training, participants in both groups were required to complete, in both testing sessions: (i) the Five Facet Mindfulness Questionnaire (FFMQ, Baer et al., 2006), a 39-item measure consisting of five subscales, respectively assessing the ability to observe, describe, act with awareness, non-judge and non-react to inner experience (Cronbach's alpha: a) FFMQ-observe: Session1 MOM = 0.85, controls = 0.79; Session2 MOM = 0.74, controls = 0.82; b) FFMQ-describe: Session1 MOM = 0.89, controls = 0.91; Session2 MOM = 0.88, controls = 0.78; c) FFMQ-awareness: Session1 MOM = 0.94, controls = 0.89; Session2 MOM = 0.52, controls = 0.79; d) FFMQ-non-judge: Session1 MOM = 0.87, controls = 0.83; Session2 MOM = 0.90, controls = 0.93; e) FFMQ-non-react: Session1 MOM = 0.65, controls = 0.78; Session2 MOM = 0.88, controls = 0.52); (ii) the Mindful Attention Awareness Scale (MAAS, Brown & Ryan, 2003), a 15-item mindfulness scale assessing global levels of attention and awareness in daily life (Cronbach's alpha MAAS: Session1 MOM = 0.89, controls = 0.80; Session2 MOM = 0.89, controls = 0.87); (iii) the Freiburg Mindfulness Inventory (FMI, Buchheld, Grossman, & Walach, 2001), a 30-item questionnaire assessing global level of mindfulness skills (Cronbach's alpha FMI: Session1 MOM = 0.86, controls = 0.87; Session2 MOM = 0.89, controls = 0.88).

For each participant and testing session, we also measured trait (T) and state (S) anxiety levels by using the State-Trait Anxiety Inventory (STAI, Spielberger et al., 1983), a widely used 40-item, multiple-choice questionnaire (Cronbach's alpha STAI-T: Session1 MOM = 0.91, controls = 0.88; Session2 MOM = 0.86, controls = 0.93; Cronbach's alpha STAI-S: Session1 MOM = 0.88, controls = 0.87; Session2 MOM = 0.92, controls = 0.92).

Moreover, we assessed anxiety experienced during the low-stress and high-stress immersive virtual environments (IVEs) (described below in section 2.3.2), using the STAI-S immediately after the virtual experiences (Cronbach's alpha low-stress IVEs: Session1 MOM = 0.95, controls = 0.91; Session2 MOM = 0.93, controls = 0.81; Cronbach's alpha high-stress IVEs: Session1 MOM = 0.95, controls = 0.95; Session2 MOM = 0.90, controls = 0.93). Overall, except for a few exceptions regarding the act with awareness and non-react FFMQ facets, Cronbach's alpha coefficients > 0.70 show a good level of internal reliability for the mindfulness and anxiety scales used in the present study.

Finally, a measure of subjective stress perceived during the low-stress and high-stress IVEs was also collected with a Visual Analogue Scale (VAS) immediately after the virtual experiences. The stress VAS consisted of an unmarked 100 mm ruler with endpoints labelled 'Not at all stressed' and 'Totally stressed'. The participants had to indicate how stressed they felt on the ruler, which thus yielded a single subjective stress score between 0 and 100.

2.3.2. Immersive Virtual Environments

Four different IVEs were designed and developed for this study by the Human-Computer Interaction Laboratory (HCI Lab), at the Department of Mathematics and Computer Science of the University of Udine (Italy). Two of them realistically reproduce an entire train station including the main building and seven tracks. The other two IVEs realistically reproduce a multi-floor school building. Participants navigated the IVEs from a first person perspective.

To display the IVEs, we employed a Sony HMZ-T1 stereoscopic head-mounted display (HMD) equipped with two 1280 x 720 screens with a field of view of 45°. The HMD was connected to a PC with a 2.67 GHz Intel Core i7 processor, 6 GB of RAM and an Nvidia GeForce GTX 480 GPU. We used an Intersense InertiaCube3 3DoF sensor attached to the HMD to track user's head movements and update the view in the IVEs accordingly.

The difference between the two IVEs reproducing the train station (and similarly between the two IVEs reproducing the school building) concerns the intended level of elicited stress. The low-stress IVEs portray a normal, daily life situation, while the high-stress IVEs portray an emergency situation. In the following, we describe the four virtual experiences in detail. Participants were asked to evacuate the school building or the station as quickly as possible in the high-stress IVEs, or were asked to explore the building or the station in the low-stress IVEs. The existence of an exit was also mentioned to participants in the low-stress IVEs; the exit could be reached by participants during the exploration if desired. To move inside the IVE, participants employed a Nintendo Nunchuck controller (Figure 1). By moving the Nunchuck's joystick forward or backward, participants walked respectively forward and backward in the virtual world; by moving the joystick to the left or to the right, participants rotated respectively counter-clockwise and clockwise.

---- Insert Figure 1 here ----

Low-stress school building. Participants explored the school building for three minutes, starting from a classroom at the top floor (Figure 2a). Participants' walking speed in the IVE was designed to replicate a natural adult walking speed (1.5 m/s). During the navigation, participants could explore any floor of the building. Participants found any door connecting two corridors open, while other doors in the building were locked, and participants could not open them. Various groups of virtual students could be seen conversing and walking around the building (Figure 2b). The simulation included sounds that are common in school buildings: students chatting and walking, doors opening and closing, and furniture being moved.

High-stress school building. This IVE uses the same school building of the previous IVE, but portrays a fire emergency situation. As previously instructed by the experimenter, participants were required to evacuate the building by following the signs placed on walls and doors, starting from the same classroom mentioned in the low-stress experience. The IVE reproduced accurately the familiar signs which are legally mandatory for public buildings in the participants' country. All the doors belonging to the evacuation path were already opened, while other doors in the building were locked, and participants could not open them. Dark and thick smoke filled the environment (Figure 2c and 2d), and there were occasional corpses of victims (on which participants could not act) lying on the floor along the evacuation path (Figure 2d). Sound included screaming people, ambulance sirens, and fire alarm sounds, and participants could also hear a virtual breathing and heartbeat sound following them that could be interpreted as interoceptive cues in the virtual experience. Such cues were also used to reflect the "health" of participants in the virtual experience. More specifically, at the beginning of the experience, users were in normal health conditions, and able to run inside the IVE (the initial speed was set at 3.25 m/s). However, as the experience progressed, the effects of smoke inhalation and fear were simulated: participants could hear themselves breathing with more and more difficulty, the intensity of the breathing sound increased with time and the frequency and the intensity of the heartbeat sound increased as well. Visual cues were also used to convey this aversive state: a red aura flashed in sync with heartbeat, and the participants' field of view was progressively reduced. Furthermore, walking speed slowed down as time passed, and at the end of the virtual experience (3 minutes after start)

participants were almost unable to move. Finally, during the 3 minutes, participants could hear the sound of three loud explosions respectively after 30, 90 and 150 s from the start.

---- Insert Figure 2 here ----

Low-stress train station. Participants started the experience inside the last coach of a train located on the last track of the train station (Figure 3a). They navigated the train station for three minutes by walking around platforms (Figure 3b) as well as inside the station lounge. To move among platforms, participants had to take underpasses, consistently with a real-world train station.

High-stress train station. This IVE uses the same train station environment, but portrays an emergency situation in which the station is hit by multiple explosions. Participants started from the same location described in the low-stress experience (Figure 3c) and had to evacuate the train station by finding a safe path through corpses, wounded people, shattered wagons, and debris (Figure 3d). Potentially stressful stimuli included sudden and loud explosions, fire and smoke, the sight of wounded people asking for help and corpses, shattered station structures, evacuation routes blocked by fire or debris. Explosions were accompanied by a loud, low-frequency sound, and the shaking of the displayed image. Remaining inside a cloud of smoke caused the reduction of the field of view, as well as intense coughing. Touching fire or metal debris produced red flashing on the screen, together with scream sounds. Some events in the IVE were triggered by particular user actions. In particular, proceeding along the track of the train station after getting off the coach caused a sudden explosion that made the track roof collapse in front of the participant. Also, in multiple occasions along the evacuation path, getting too close to a tank wagon on fire caused its explosion, which was accompanied by a brief white flash on the screen and a few seconds long whistle that simulated a tinnitus effect. In addition to these stimuli, we further added the sound of three loud explosions that were played after 30, 90 and 150 s respectively from the beginning of the 3-min experience.

---- Insert Figure 3 here ----

2.3.3. Physiological measures

Physiological data were recorded with a Thought Technology ProComp Infiniti encoder and Biograph Infiniti software (Thought Technology, 2014). The following physiological variables were acquired for each participant during both testing sessions:

Heart rate and blood volume pulse amplitude. Cardiovascular activity was recorded through a photoplethysmograph placed on the distal phalanx of the index finger of the left hand. The blood volume pulse signal was sampled at 256 Hz; heart rate (HR) and blood volume pulse amplitude (BVPA) values were calculated in real time by the Biograph Infiniti software. Increases in HR are generally related to emotional activation (Andreassi, 2007), and the studies mentioned in Bradley and Lang (2007) indicate that, in the case of visual stimuli, heart rate acceleration varies consistently with stimulus arousal, increasing with both pleasant and unpleasant arousing stimuli. An increase in BVPA is related to a decreased vasoconstriction and a state of relaxation, while a decrease in BVPA is related to states such as pain, hunger, fear and rage (Frijda, 1986).

Facial electromyography. Facial electromyography (EMG) was recorded through two disposable sets of Ag/AgCl electrodes. Each set was composed of a positive, a negative, and a ground electrode. The six electrodes were placed on the skin of participants' face following the guidelines presented in Tassinary, Cacioppo, and Vanman (2000) in order to record the surface activity of the left zygomaticus major and the left corrugator supercilii muscles. Raw EMG signal was filtered in real time using Biograph Infinity: first, a band-pass filter between

10 and 500 Hz was applied to isolate the electrical activity of interest as suggested in Van Boxtel (2001); a band-stop filter around the 50 Hz frequency was also automatically applied by Biograph Infiniti to remove any electrical noise coming from the power line. The filtered signal was then rectified through a RMS filter with a non-sliding window of 10 signal samples. Andreassi (2007) discussed various studies in the literature that strongly relate the activity of zygomaticus major and corrugator supercilii muscles to positively- and negatively-valenced emotional stimuli respectively (see also Schwartz, Ahern, & Brown, 1979; Larsen, Norris, & Cacioppo, 2003).

Respiratory frequency. An elastic girth sensor was placed over the participants' chest to measure respiration frequency (respiratory rate), expressed as breaths per minute (BPM). It is known that sympathetic arousal contributes to changes in respiration frequency (Lorig, 2007).

Skin conductance level. Electrodermal activity (EDA) was recorded through a pair of Ag/AgCl electrodes placed on the intermediate phalanges of index and middle fingers of the left hand. The signal was sampled at 256 Hz, and decomposed off-line to get the tonic component of the signal, corresponding to skin conductance level (SCL), using Ledalab (Benedek & Kaernbach, 2010). Changes in skin conductance can be produced by various physical and emotional stimuli that trigger variations in the eccrine sweat gland activity that, unlike many other bodily functions, is controlled exclusively by the sympathetic nervous system (Boucsein, 2006), making EDA an appropriate physiological signal for arousal measurement. Also, the slow-changing nature of the EDA signal makes electrical interferences and artifacts (caused, for example, by participants' movements) easily detectable and removable.

For each physiological variable (HR, BVPA, zygomaticus major EMG, corrugator supercilii EMG, BPM, SCL), we calculated its mean value and standard deviation over the duration (3 min) of each of the four IVE experiences and for the 1 min baseline periods that were recorded before each IVE.

2.4. Experimental procedure

Both groups were administered the IVE tasks and questionnaires in two separate sessions. Participants were tested individually, in a quiet room. The experimenter described to each participant the IVE tasks in terms of environment (school building or train station), duration, goals, and the use of the Nunchuck joystick. Participants were also informed about the HMD and the physiological sensors used during the test. In both testing sessions, each participant first completed the questionnaires in the following order: FFMQ, FMI, MAAS, STAI (state and trait). Then, the skin of participants' left hand, left cheek, and left part of forehead was cleaned using a cotton pad and denatured alcohol and the physiological sensors were applied. Next, participants wore the HMD and they were asked to hold the joystick with the right hand. They sat in a comfortable position and were asked to relax for about 2 min, while the baseline for the physiological signals was recorded. For the statistical analyses, we considered the central minute of this recording as baseline. During the entire 2-min period, participants could close their eyes, relax and breathe normally.

Participants were then administered one of the two Low-stress IVE 3-min experiences. In each group of participants, half participants used the Low-stress school building IVE, while the second half were administered the Low-stress train station IVE. The reverse order was followed in the second testing session: participants who had experienced the Low-stress school building IVE (resp. train station) in the first session were administered the Low-stress train station IVE (resp. school building) in the second testing session. After the Low-stress IVE experience, the HMD was removed and participants were asked to complete the STAI-S and the stress VAS. Next, the HMD was worn again and another 2-min baseline period was recorded following the same procedure of the first baseline period.

Finally, participants were administered a 3-min High-stress IVE experience: if they had used the Low-stress train station (resp. Low-stress school building) in that session, then the second virtual experience of the session was the High-stress train station (resp. High-stress school building). As a result, the same balancing procedure adopted for the Low-stress IVEs was followed for the High-stress IVEs: participants who were presented with the High-stress train station (resp. High-stress school building) IVE in the first testing session used the High-stress school building (resp. High-stress train station) IVE in the second testing session. The overall procedure ensured that each participant of both groups (MOM and control) interacted with the train station and school building in the Low- and High-stress versions across the two testing sessions to counterbalance possible learning effects and ruling out the possibility that any MOM-related (physiological and behavioral) effect could be due to differences in elicited stress and arousal among the school building and train station IVEs. After the High-stress IVE, each participant completed again the STAI-S and stress VAS, then all physiological sensors were removed. Participants were finally thanked and offered the opportunity to ask any question about what they had experienced during the whole experiment. The overall procedure (including filling the questionnaires) took altogether around 50-60 minutes for each of the two sessions.

2.5. Data analysis

The data were analyzed with Statistica 8 (StatSoft, Inc, Tulsa, OK). The main analyses concerned a series of mixed model ANOVAs. For the mindfulness and STAI (State and Trait) questionnaires, the ANOVAs included Session (Session1, Session 2) as within-subject factor and Group (MOM, control) as between-subject factor. The dependent variables were the measures obtained for the FMI, the MAAS, the STAI-S and STAI-T, and for the five facets included in the FFMQ.

For the physiological measures, a mixed model ANOVA was carried out for each measure (HR, BVPA, corrugator supercilii EMG, zygomaticus major EMG, BPM, and SCL), with Session (Session1, Session 2) and level of stress in the IVE (Low-stress, High-stress) as within-subject factors, and Group (MOM, control) as between-subject factor. For each physiological measure, we considered as dependent variable the data obtained by subtracting the baseline value recorded immediately before using an IVE from the recorded values during that IVE experience. Such subtraction is necessary to account for differences in individual basic arousal levels (Andreassi, 2007).

Before running these analyses, we tested whether the IVEs used in this study actually differed in the level of perceived stress and state anxiety. In particular, we considered the STAI-S and stress VAS (both completed immediately after the Low-stress and High-stress IVEs), and analyzed them with two mixed model ANOVAs involving Session (Session1, Session 2) and level of stress in the IVE (Low-stress, High-stress) as within-subject factors, and Group (MOM, control) as between-subject factor. Moreover, in a series of supplementary analyses, we also tested for possible differences between the school building and the train station IVEs.

A 0.05 significance threshold was used in all statistical tests. In all ANOVAs, significant interactions were followed-up with Duncan's post hoc tests. In the analyses, effect sizes are reported as partial eta squared (η_p^2).

3. Results

3.1. Low-stress and High-stress IVEs: analyses of STAI-S and stress VAS

We assessed state anxiety and stress levels after Low-stress and High-stress IVEs by using the STAI-S and the stress VAS. The 2 (Session: Session1, Session2) x 2 (IVE: Low-stress, High-stress) x 2 (Group: MOM, control) ANOVA carried out for the STAI-S showed a main

effect of IVE (F (1, 34) = 30.09, p < .01; η_p^2 = .47; observed power = .99) indicating higher scores (i.e., higher state anxiety) after High-stress rather than Low-stress IVEs (see Fig. 4A). All other main effects and interactions did not reach significance (for all, F (1, 34) < 3.96, p > .05; η_p^2 < .11; observed power < .49). The ANOVA performed for the stress VAS also showed a main effect of IVE (F (1, 34) = 28.14, p < .01; η_p^2 = .45; observed power = .99), denoting higher perceived stress after High-stress than Low-Stress IVEs (see Fig. 4B). All other main effects and interactions involving the stress VAS data did not reach significance (for all, F (1, 34) < 2.32, p > .13; η_p^2 < .07; observed power < .32). These results indicate that the IVEs used in this study actually differed in the level of perceived stress, with High-Stress IVEs subjectively eliciting higher state anxiety and stress than Low-stress IVEs. Nevertheless, there were no differences between groups in these subjective measures, suggesting that MOM training had no significant effect in modulating perceived state anxiety and stress levels immediately after IVE experiences.

In view of these results, we repeated similar analyses this time taking into consideration each of the two different IVEs (i.e., school building and train station). Because of our balancing procedure adopted for the school building and the train station IVEs, these supplementary analyses were carried out separately for the two sessions (note also the non-significant effect of the factor Session in the previous analyses). The 2 (IVE: Low-stress, High-stress) x 2 (Group: MOM, control) x 2 (IVE-type: school building, train station) ANOVA carried out for the STAI-S data at Session1 showed a main effect of IVE (F (1, 32) = 21.56, p < .01; η_p^2 = .40; observed power = .99) indicating higher state anxiety after High-stress than Low-stress IVEs. All other main effects and interactions did not reach significance (for all, F (1, 32) < 1.49, p > .23; η_p^2 < .05; observed power < .22). Thus, no main effect or interaction involving the IVE-type factor was found. The ANOVA performed for the STAI-S data at Session2 also showed a main effect of IVE (F (1, 32) = 18.17, p < .01; η_p^2 = .36; observed power = .98), but no other main effects or interactions (for all, F (1, 32) < 0.55, p > .46; η_p^2 < .02; observed power < .12). Next, we ran two corresponding ANOVAs for the stress VAS data. Similarly to the analyses of the STAI-S data, for both Session1 and Session2, the analyses carried out for the stress VAS only showed a main effect of IVE denoting higher perceived stress after High-stress than Low-Stress IVEs (F (1, 32) = 17.65, p < .01; η_p^2 = .36; observed power = .98 and F (1, 32) = 11.01, p < .01; η_p^2 = .26; observed power = .89, respectively for Session1 and Session2), but not other main effects or interactions (for all, F (1, 32) < 1.38, p > .24; η_p^2 < .05; observed power < .21).

Overall, these results indicate that there were no significant differences between the school building and the train station IVEs in terms of elicited levels of perceived stress and state anxiety, with High-Stress IVEs eliciting higher scores than Low-stress IVEs.

---- Insert Figure 4 here ----

3.2. Dispositional mindfulness and STAI (trait and state) data

The 2 (Session: Session1, Session2) x 2 (Group: MOM, control) repeated measure ANOVA carried out for the FMI questionnaire did not show significant main effects of Group (F (1, 34) = .20, p = .65; η_p^2 = .01; observed power = .07) or Session (F (1, 34) = 1.55, p = .22; η_p^2 = .04; observed power = .23), but pointed out a significant interaction (F (1, 34) = 17.52, p < .01; η_p^2 = .34; observed power = .98), indicating that dispositional mindfulness changed differently from the first to the second session in the two participant groups. Post-hoc tests carried out to analyze this two-way interaction revealed an increase in FMI scores (i.e., Session2 vs. Session1) in the MOM group (p < .01) but not in the control group (p > .05) (see Fig. 5A).

A similar 2 x 2 ANOVA performed for the MAAS questionnaire did not show significant main effects or interaction (for all, $F(1, 34) < 1.39$, $p > .24$; $\eta_p^2 < .04$; observed power < .21) (see Fig. 5B). This indicates no significant modulatory effects of the MOM training on the trait mindfulness levels that are measured by the MAAS questionnaire.

For the FFMQ, we performed a 2 (Session) x 2 (Group) repeated measures ANOVA for each of the 5 facets. A significant interaction between Session and Group was found for the "observe" facet ($F(1, 34) = 15.53$, $p < .01$; $\eta_p^2 = .31$; observed power = .97). Post-hoc tests performed for this interaction showed higher scores in this facet for MOM participants at Session2 vs. Session1 ($p < .01$) and higher scores for MOM vs. control at Session2 ($p < .03$). Interactions and main effects for the remaining four facets (describe, act with awareness, non-judge and non-react) were not statistically significant (for all, $F(1, 34) < 3.33$, $p > .07$; $\eta_p^2 < .09$; observed power < .43). For main effects, however, the only significant effect concerned Session ($F(1, 34) = 8.29$, $p < .01$; $\eta_p^2 = .20$; observed power = .80) for the "non-judge" facet, indicating higher values, globally for the two groups, at Session2 vs. Session1 (see Fig. 5C).

For STAI-S and STAI-T data, we ran two separate 2 (Session: Session1, Session2) x 2 (Group: MOM, control) repeated measures ANOVAs. The analysis of STAI-T data highlighted a main effect of Session ($F(1, 34) = 10.08$, $p < .01$; $\eta_p^2 = .23$; observed power = .87) and a two-way interaction ($F(1, 34) = 5.51$, $p < .03$; $\eta_p^2 = .14$; observed power = .62). The main effect of Group was instead not significant ($F(1, 34) = .28$, $p = .60$; $\eta_p^2 = .01$; observed power = .08). Post-hoc analysis of the interaction showed significantly lower STAI-T scores at Session2 vs. Session1 in MOM participants ($p < .01$), but not in controls ($p = .56$) (see Fig. 5D). The analysis of STAI-S data showed no significant main effect of Group ($F(1, 34) = .34$, $p = .56$; $\eta_p^2 = .01$; observed power = .09) or Session ($F(1, 34) = .02$, $p = .90$; $\eta_p^2 < .01$; observed power = .05) and a significant two-way interaction ($F(1, 34) = 4.15$, $p < .05$; $\eta_p^2 = .11$; observed power = .51). Although post-hoc tests performed for the STAI-S did not reach significance, the interaction mediated the tendency of MOM participants to show lower levels of state anxiety at Session2 vs. Session1, together with the opposite tendency in controls (see Fig. 5E).

In sum, the analyses of the mindfulness and STAI questionnaires showed specific effects of the MOM training in increasing both global (i.e., FMI scores) and specific mindfulness skills. In particular, MOM participants self-reported increased abilities to observe inner mental and somatosensory experience after the training (i.e., the "observe" factor in the FFMQ). However, no change was observed in trait mindfulness of MOM and control participants, as measured through the MAAS scale. Finally, MOM participants reported decreased trait and state anxiety levels after the meditation course, while controls tended to have higher state anxiety at the beginning of the second vs. the first testing session.

---- Insert Figure 5 here ----

3.3. Analysis of physiological data

3.3.1. Heart rate and blood volume pulse amplitude

The baseline values recorded before and the physiological values recorded during IVE experiences are reported in Table 1 for the two groups and the two testing sessions, for each physiological measure. As previously explained, the following analyses require subtraction of baseline values from the values recorded during IVE experiences. The 2 (Session: Session1, Session2) x 2 (IVE: High-stress, Low-stress) x 2 (Group: MOM, control) ANOVA carried out for HR data showed main effects of Session ($F(1, 34) = 12.58$, $p < .01$; $\eta_p^2 = .27$; observed power = .93) and IVE ($F(1, 34) = 31.51$, $p < .01$; $\eta_p^2 = .48$; observed power = .99) as well as their interaction ($F(1, 34) = 6.89$, $p < .02$; $\eta_p^2 = .17$; observed power = .72). Post-hoc analysis

of the interaction indicated a significant difference in HR during the two different types of IVEs (HR in High-stress IVEs > HR in Low-Stress IVEs) in Session1 ($p < .01$) but not in Session2 ($p = .20$), and a difference across the two sessions in the High-stress IVE (HR in Session1 > HR in Session2, $p < .01$). More interestingly, there was an interaction between Session and Group ($F (1, 34) = 4.32$, $p < .05$; $\eta_p^2 = .11$; observed power = .52), indicating a decrease in HR in Session2 with respect to Session1 in MOM participants ($p < .01$), but not in controls ($p = .31$) (see Fig. 6A). The fact that there was no three-way interaction involving the IVE factor ($F (1, 34) = .03$, $p = .86$; $\eta_p^2 < .01$; observed power = .05) indicated that the decrease in HR observed in MOM participants after participation in MOM training occurred for both High- and Low-stress IVEs. Globally, these results indicate emotional deactivation and reduced arousal in MOM subjects while facing IVEs for the second time. All other main effects and interactions for HR were not statistically significant (for all, $F (1, 34) < 1.80$, $p > .18$; $\eta_p^2 < .06$; observed power < .26).

The 2 x 2 x 2 ANOVA carried out for the BVPA data did not produce instead significant main effects or interactions (for all, $F (1, 34) < 3.37$, $p > .07$; $\eta_p^2 < .10$; observed power < .43).

3.3.2. Facial electromyography

The 2 x 2 x 2 ANOVA carried out for the corrugator supercilii muscle showed a main effect of IVE (higher activity of the muscle for High- vs. Low-stress IVEs; $F (1, 34) = 12.21$, $p < .01$; $\eta_p^2 = .26$; observed power = .92) and an interaction between Group and Session ($F (1, 34) = 6.75$, $p < .02$; $\eta_p^2 = .17$; observed power = .71). Although post-hoc tests performed for this interaction did not show statistically significant changes in muscle activity as a function of testing session (all $p > .05$), the interaction was mediated by the tendency of MOM participants to show lower levels of corrugator supercilii muscle activity at Session2 vs. Session1 while controls displayed an opposite trend. Moreover, MOM and controls tended to differ in this muscle activity particularly at Session2 (see Fig. 6B). Globally, the interaction between Group and Session suggests a role of MOM in determining reduced activity in a muscle generally related to negatively-valenced emotional stimuli. The three-way interaction involving the IVE factor was not statistically significant ($F (1, 34) = 1.00$, $p = .32$; $\eta_p^2 = .03$; observed power = .16), indicating that this effect of MOM involved IVEs with different levels of perceived stress. All other main effects and interactions in the ANOVA of corrugator supercilii muscle data were not statistically significant (for all, $F (1, 34) < .53$, $p > .47$; $\eta_p^2 < .02$; observed power < .11).

The 2 x 2 x 2 ANOVA of zygomaticus major muscle data did not show any significant main effect or interaction (for all, $F (1, 34) < 3.74$, $p > .06$; $\eta_p^2 < .10$; observed power < .47).

3.3.3. Respiration frequency

The 2 x 2 x 2 ANOVA performed for the respiration frequency measure (BPM) showed a main effect of Session (BPM Session1 > BPM Session2; $F (1, 34) = 6.58$, $p < .02$; $\eta_p^2 = .16$; observed power = .70) and IVE (BPM High-stress < BPM Low-stress; $F (1, 34) = 7.04$, $p < .02$; $\eta_p^2 = .17$; observed power = .73), but not a main effect of Group or interactions between factors (for all, $F (1, 34) < 2.60$, $p > .11$; $\eta_p^2 < .08$; observed power < .35).

3.3.4. Skin conductance level

Two control participants were excluded from the analysis, because the sensors placed on the left hand failed to record SCL (i.e., a value of 0 was obtained throughout the entire recording during the two IVEs: this happened at Session1 for one subject and at Session2 for another subject). The 2 x 2 x 2 ANOVA performed for the SCL measure returned a main effect of IVE (SCL High-stress < SCL Low-stress; $F (1, 32) = 10.93$, $p < .01$; $\eta_p^2 = .25$;

observed power = .89). All other main effects and interactions were not statistically significant (for all, $F(1, 32) < 2.48$, $p > .12$; $\eta_p^2 < .08$; observed power < .34).

---- Insert Figure 6 and Table 1 here ----

4. Discussion

The goal of the current study was to investigate how meditators respond to stressful situations that simulate in controlled conditions emergencies that may occur in real-world circumstances. To this end, VR was used as an ecological research instrument to study the psychological and physiological responses evoked by a series of IVEs (either reproducing a train station or a school building and differing in the levels of perceived anxiety and stress; i.e., low-stress and high-stress IVEs). Two groups of participants were considered: the MOM group was involved in an 8-week MOM course, while the control group was not involved in any meditation course. Self-report measures of mindfulness and anxiety showed specific increases in mindfulness skills (e.g., the "observe facet" in the FFMQ and the global mindfulness score calculated by the FMI) and decreased trait and state anxiety levels (STAI-S and STAI-T) in MOM vs. control participants at Session2 vs. Session1. Also, we found a decrease in HR in Session2 vs. Session1 in MOM participants but not in controls and a corresponding reduction in the activity of the corrugator supercilii muscle, which is a muscle generally associated to negatively-valenced emotional stimuli, in MOM vs. control participants. It is worth noting that these physiological results were not influenced by the level of subjectively perceived stress elicited by the IVEs. Finally, the other recorded physiological parameters (i.e., BVPA, electromyography of the zygomaticus major muscle, BPM and SCL) did not differ between MOM and controls.

Overall, the results highlighted by the self-report questionnaires are consistent with findings obtained using similar MOM protocols (Shapiro, Schwartz, & Bonner, 1998; Carmody & Baer, 2008; Crescentini et al., 2014; see also Brown & Ryan, 2003), suggesting that the MOM course was effective in positively influencing psychological well-being, by increasing mindfulness skills and decreasing anxiety.

Most previous research on mindfulness-based interventions has usually focused on self-report measures to characterize the positive effects on psychophysical health. Nevertheless, a series of studies have recently included physiological measures to further study the mechanism underlying the observed health improvement, suggesting that mindfulness may lead to decreased physiological arousal and better autonomic regulation (e.g., parasympathetic cardiac control and respiration) (e.g., Solberg et al., 2000; Young & Taylor, 2001; Rubia, 2009; Delgado et al., 2010; Zeidan et al., 2010; see also Introduction). It must be noted that these suggestions have usually been put forward by detecting changes in transient state mindfulness that can arise during and shortly after MM periods or, as in Delgado et al. (2010), by recording physiological parameters in meditators during simple "passive" tasks such as listening intense white noise capable of eliciting cardiac defence (Non-cued defence response paradigm) or while looking at pictures with different valence and arousal scores (Cued startle probe paradigm). The current study was the first to use immersive virtual reality to simulate low- and high-stress situations that can occur in real life while recording a set of physiological parameters in MOM and control participants. Overall, the results obtained for the HR and the corrugator supercilii muscle may be interpreted as indicating a role of MOM in promoting reduced arousal and emotional deactivation while participants faced stressful IVE experiences. As already mentioned, the activation of the corrugator muscle has been shown to

increase and decrease respectively with negative and positive affect (Larsen, Norris, & Cacioppo, 2003; see also Lang, Greenwald, Bradley, & Hamm, 1993). For example, reduced corrugator activity has been reported in the acceptance and cognitive reappraisal conditions of a study in which healthy subjects were presented with films clips eliciting aversive emotional states (i.e., fear, disgust and sadness; Wolgast, Lundh, & Viborg, 2011); moreover, in other studies, decreased corrugator activity was observed when healthy participants intentionally reduced negative affect elicited by neutral and negative pictures (Lee, Shackman, Jackson, & Davidson, 2009; Ray, McRae, Ochsner, & Gross, 2010).

The present results are unlikely to mainly reflect changes in transient state mindfulness but rather could be due to lasting changes in individuals' trait mindfulness that can persist in MOM participants irrespective of being actively engaged in meditation practice (Cahn & Polich, 2006; Brown, Ryan, & Creswell, 2007). Indeed, participants in the current study were not explicitly asked to be mindful or meditate before or during the IVE experiences. Moreover, in the second testing session they were tested on average after more than 12 days from the MOM course end date to not interfere with state mindfulness levels. More generally, the MOM course allowed participants to face IVE experiences in a state characterized by increased mindfulness skills (FMI, FFMQ), reduced state and trait anxiety and better physiological, and possibly emotional, regulatory mechanisms. These effects were likely promoted by the two fundamental factors of mindfulness that are believed to lead to improved emotional stability, namely self-regulation of attention (awareness) and non-judgmental/acceptance of internal and external aspects of present-moment experience (Bishop et al., 2004; Chambers, Gullone, & Allen, 2009).

As discussed, the present findings extend in a number of important ways the results of previous studies that tried to combine self-report measures and physiological responses with the aim to better identify the mechanisms underpinning the beneficial health effects of MM. Furthermore, they also highlight the importance of using ecologically valid, real-world applications of immersive VR systems for pinpointing the health effects of MM. This approach could help to further corroborate empirically any possible benefit of MM in developing new and more healthy and adaptive ways to experience and face daily life events (Kabat-Zinn, 1990; Crescentini & Capurso, 2015). In fact, in the context of MM research so far, VR has usually been limited to applications capable to promote the adoption of meditative, or meditation-related, states in healthy subjects (Vidyarthi & Riecke, 2014; Falconer et al., 2014; see also Hudlicka, 2013). Nevertheless, another important area where VR is increasingly being applied concerns the treatment of psychological and mental health disorders. As a few representative examples, VR has been employed effectively for enhancing existing interventions in a variety of medical conditions ranging from exposure therapy for phobia desensitization (North, North, & Coble, 1996), chronic and acute pain (Wiederhold, Soomro, Riva, & Wiederhold, 2014), post-stroke rehabilitation (Imam & Jarus, 2014), post-traumatic stress disorder (Gerardi et al., 2010; McLay et al. 2014), and anxiety disorders (Rothbaum & Hodges, 1999; Diemer et al., 2014; McCann et al., 2014).

In addition to suggesting the usefulness of VR for future studies aimed at maximizing the beneficial effects of MOM interventions, our study indicates that it may be worthwhile to explore the use of VR applications, together with psychophysiological measures, as a tool to evaluate the effects of MM on complex, real-world behaviors, such as those taking place in stressful, emergency situations or also in social situations that call for prosocial behavior (Zanon et al., 2014).

A number of limitations and suggestions for future research need to be borne in mind when evaluating the theoretical and practical implications of our findings. The first issue concerns the specific IVE experiences we used. Our study could have employed additional validation indices, such as behavioral indices based on navigation behavior expressed in terms of, for

example, frequency of collisions with objects in low- and high-stress IVEs or frequency of backward movements while moving toward the exit in the IVEs. Gamberini et al. (2015) provided an example of such behavioral indices of effectiveness of IVEs, used together with self-reports, but however did not consider physiological measures. Beyond contributing to further validate the present IVEs, such behavioral indices might quantify the pattern of response to emergency situations produced by meditators vs. controls. With regard to the physiological indices, some potential confounding could have occurred in association with the fixed sequence of the low-stress and high-stress IVEs. A counterbalanced order might have provided more pronounced physiological differences between the two types of IVEs in the current study, although the low-stress IVE could have been perceived as too little engaging when occurring after the high-stress IVE.

Another issue pertains to sample size and type of experimental design used in our study. First, the relative small sample size raises issue of generalizability of the obtained results and indicates the need to extend the current findings to larger samples of meditators and controls. Although less powerful than longitudinal designs, cross-sectional studies comparing expert meditators with naïve or less expert participants would also be informative with respect to beneficial effects of MM in responding to virtual simulations of real-life emergencies. Second, the inclusion of a non-treatment (non-active), waiting-list control group in our study has allowed controlling for the non-specific effects of the time elapsed between the two testing sessions but, at the same time, makes it more difficult to finally ascribe to meditation practice the changes observed in MOM participants. The latter participants, indeed, received more than MOM practice, having for instance the opportunity to create a fairly intimacy-inducing community. In other words, the difference between MOM and controls in aspects other than MOM practice could have influenced the way in which MOM participants experienced IVEs in our study. Thus, it is desirable for future research aimed at using IVEs in MM studies to benefit from more rigorous active control conditions (e.g., Delgado et al., 2010; MacCoon et al., 2012), as well as follow-up assessments that, unlike our study, might also allow investigating how long-lasting the changes observed in MOM participants could be.

In conclusion, the present study tested the effects of an 8-week mindfulness meditation program on the psychological and physiological responses evoked by immersive virtual environments, characterized by different levels of elicited stress, which simulated emergency situations that can occur in real life. We showed that continued meditation practice over a period of two months led to increased mindfulness skills and reduced state and trait anxiety, as well as to better physiological and emotional regulation during IVE experiences. These findings were held to be promoted by the two fundamental factors of mindfulness, namely awareness and non-judgmental/acceptance of present-moment experience. Finally, we believe that future studies aimed at further investigating the mechanisms underlying the health effects of MM in both clinical and non-clinical populations should continue to combine psychological and physiological indices of well-being with ecologically valid, real-world applications of immersive VR systems in an effort to increase our understanding of how MM can have a profound impact on day-to-day life.

Disclosure Statement

The authors report no conflicts of interest.

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Table 1. Physiological data recorded during baseline and IVEs periods in testing sessions 1 and 2, for MOM and control participants.

Physiological measure	Session1 Baseline1	Session1 Baseline2	Session1 Low-stress IVE	Session1 High-stress IVE	Session2 Baseline1	Session2 Baseline2	Session2 Low-stress IVE	Session2 High-stress IVE
HR								
MOM	75.23	73.85	77.42	81.29	74.24	75.51	75.22	77.07
	(13.63)	(12.78)	(15.48)	(14.88)	(16.06)	(14.59)	(16.81)	(15.53)
Controls	75.69	74.87	76.20	82.14	72.27	73.27	73.88	77.57
	(12.15)	(10.51)	(13.51)	(14.64)	(7.27)	(7.45)	(9.10)	(11.29)
BVPA								
MOM	3.77	3.56	3.61	2.98	6.56	6.84	6.88	5.79
	(3.80)	(2.71)	(3.08)	(2.35)	(4.02)	(3.19)	(3.57)	(3.23)
Controls	3.71	3.37	2.84	2.70	6.10	5.43	4.59	4.01
	(2.58)	(2.35)	(1.80)	(1.57)	(3.39)	(3.17)	(2.91)	(2.67)
Corrugator supercilii								
MOM	4.47	4.16	3.78	5.23	4.52	5.02	3.73	4.87
	(2.77)	(1.78)	(1.21)	(2.49)	(1.98)	(3.46)	(1.19)	(2.57)
Controls	4.25	4.36	3.65	4.72	4.67	4.19	4.74	5.39
	(2.06)	(2.39)	(2.10)	(3.61)	(2.43)	(1.85)	(3.59)	(3.57)
Zygomaticus major								
MOM	2.78	2.79	4.55	4.73	2.69	2.81	6.27	3.68
	(1.05)	(0.98)	(1.85)	(2.70)	(1.33)	(1.31)	(8.52)	(1.85)
Controls	2.29	2.33	3.93	4.47	2.52	2.48	4.01	4.26
	(0.92)	(0.85)	(1.87)	(1.87)	(0.81)	(1.06)	(1.75)	(2.43)
BPM								
MOM	8.88	9.75	15.55	15.13	10.44	11.69	15.49	16.12
	(2.47)	(3.05)	(1.87)	(2.48)	(3.12)	(3.74)	(2.41)	(2.25)
Controls	11.73	11.95	16.54	16.24	12.41	13.19	16.23	15.70
	(2.40)	(2.69)	(1.76)	(1.73)	(3.50)	(3.38)	(1.33)	(1.65)
SCL								
MOM	1.91	3.50	3.09	4.24	2.06	3.84	3.17	4.37
	(1.38)	(2.26)	(2.28)	(2.54)	(2.23)	(3.02)	(2.76)	(3.10)
Controls*	1.34	2.70	2.45	3.24	1.32	2.94	2.48	3.75
	(1.03)	(2.39)	(2.05)	(2.80)	(0.91)	(2.79)	(2.11)	(3.28)

Notes: IVE = Immersive Virtual Environment; Baseline1 occurred before Low-stress IVE; Baseline2 occurred before High-stress IVE and after Low-stress IVE; MOM = Mindfulness-Oriented Meditation; HR = Heart Rate; BVPA = blood volume pulse amplitude; BPM = breaths per minute; SCL = skin conductance level. *Two controls were excluded from SCL analysis (see main text for further details). Standard deviations of the means are reported in parentheses.

Figure 1. The Nintendo Nunchuck controller employed in the study.

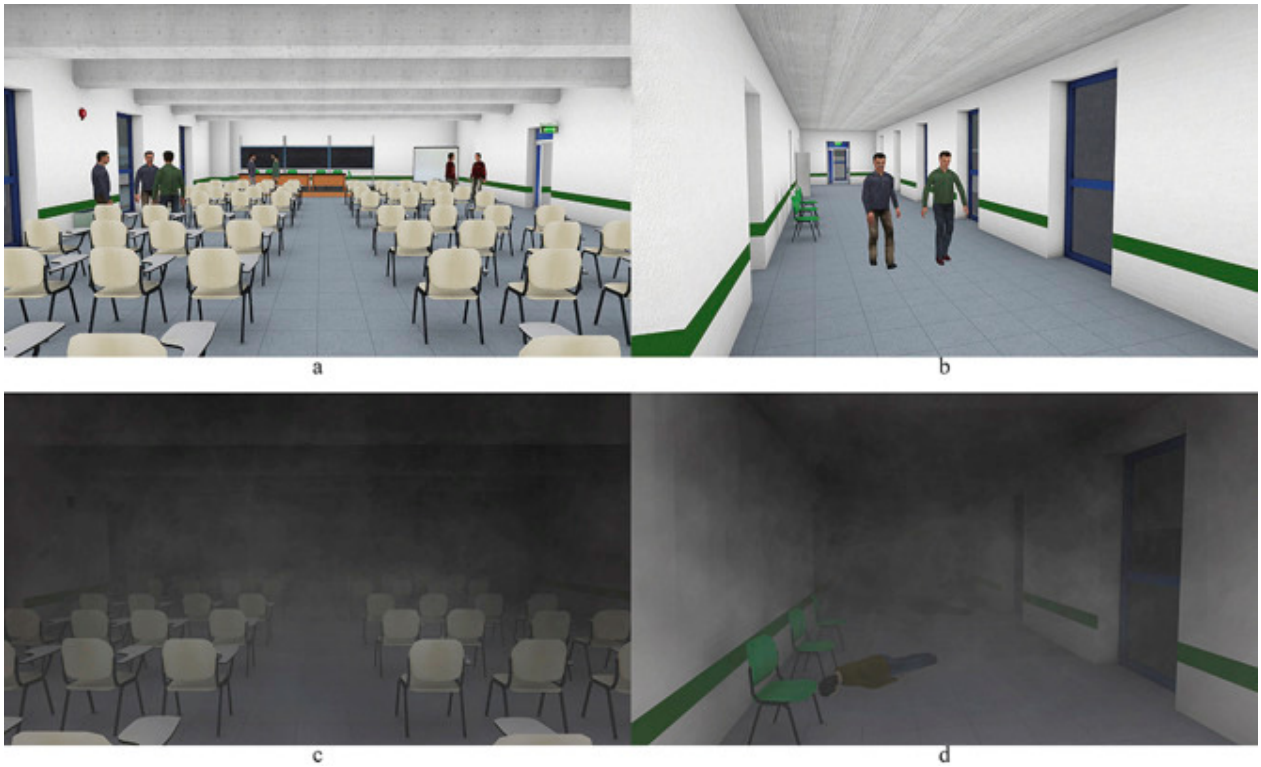

Figure 2. Screenshots of the low-stress (a and b) and the high-stress (c and d) school building IVEs: the classroom in which participants are located at the beginning of the two IVEs (a and c), and a corridor in the building (b and d).

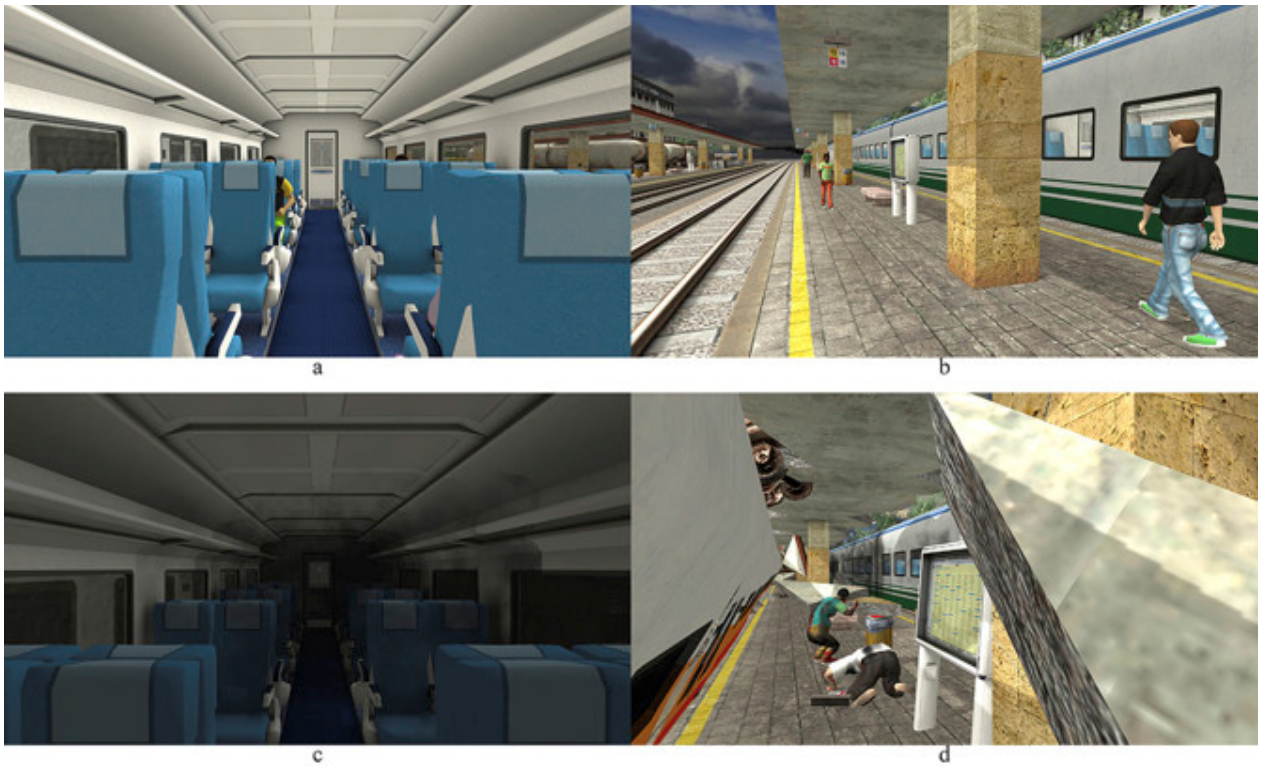

Figure 3. Screenshots of the low-stress (a and b) and the high-stress (c and d) train station IVEs: the coach in which participants are located at the beginning of the two IVEs (a and c), and a view of a train platform (b and d).

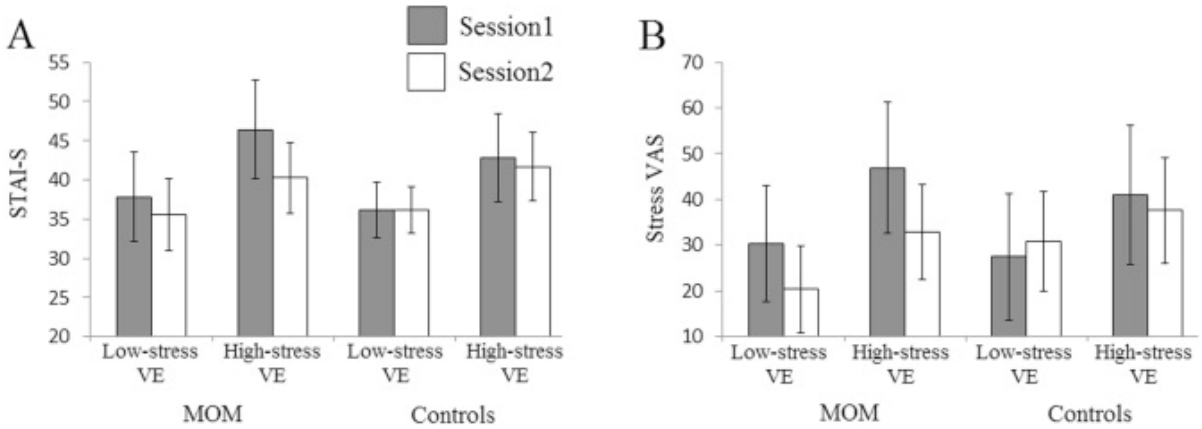

Figure 4. A) STAI-S raw scores in MOM and control participants for the two testing sessions and for the Low- and High-stress IVEs; B) Stress VAS raw scores in MOM and control participants for the two testing sessions and for the Low- and High-stress IVEs. Vertical bars denote standard deviations.

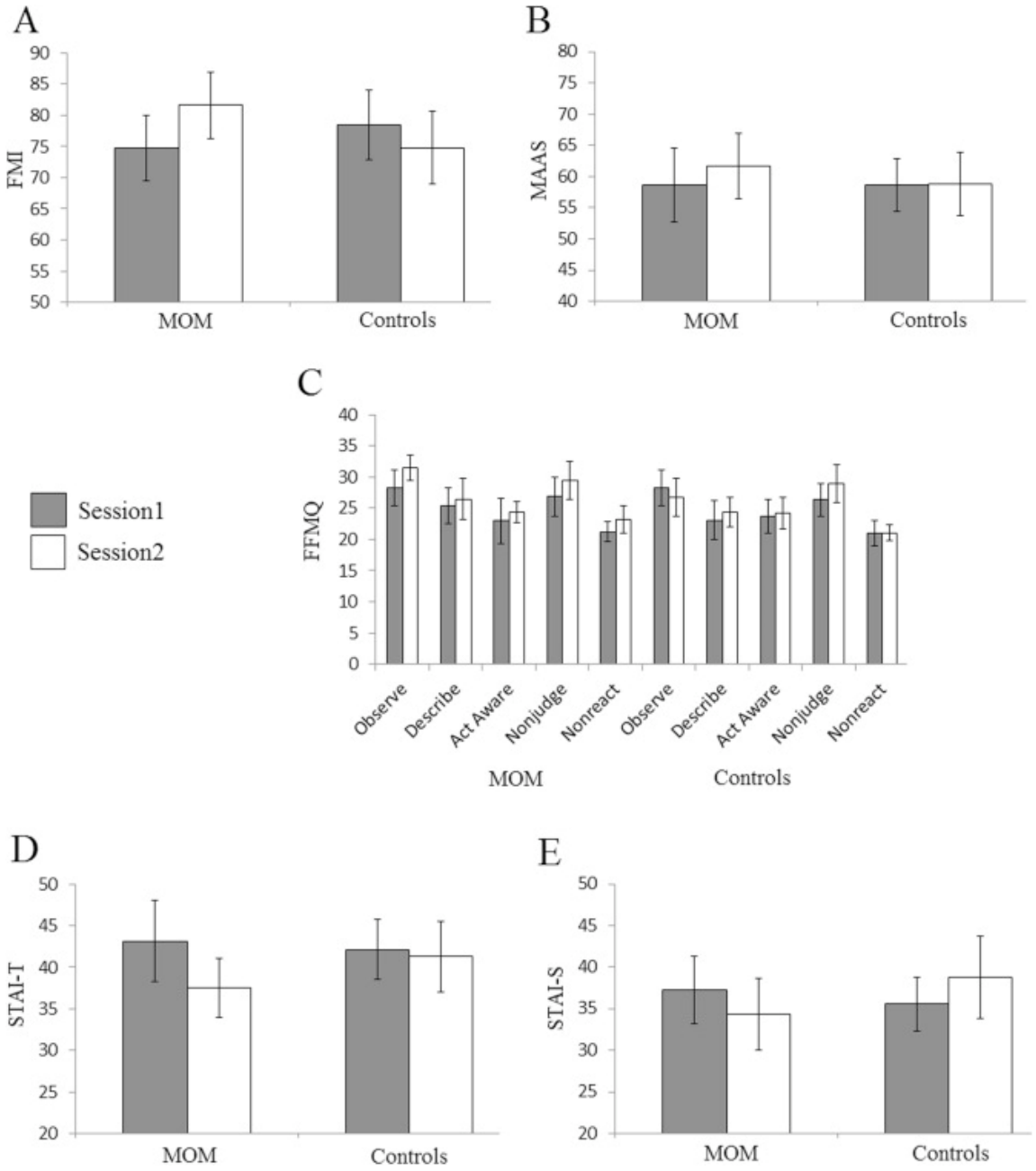

Figure 5. A) Freiburg Mindfulness Inventory (FMI) raw scores in MOM and control participants for the two testing sessions; B) Mindful Attention Awareness Scale (MAAS) raw scores in MOM and control participants for the two testing sessions; C) Five Facet Mindfulness Questionnaire (FFMQ) raw scores in MOM and control participants for the two testing sessions; D) STAI-T raw scores in MOM and control participants for the two testing sessions; E) STAI-S raw scores in MOM and control participants for the two testing sessions. Vertical bars denote standard deviations.

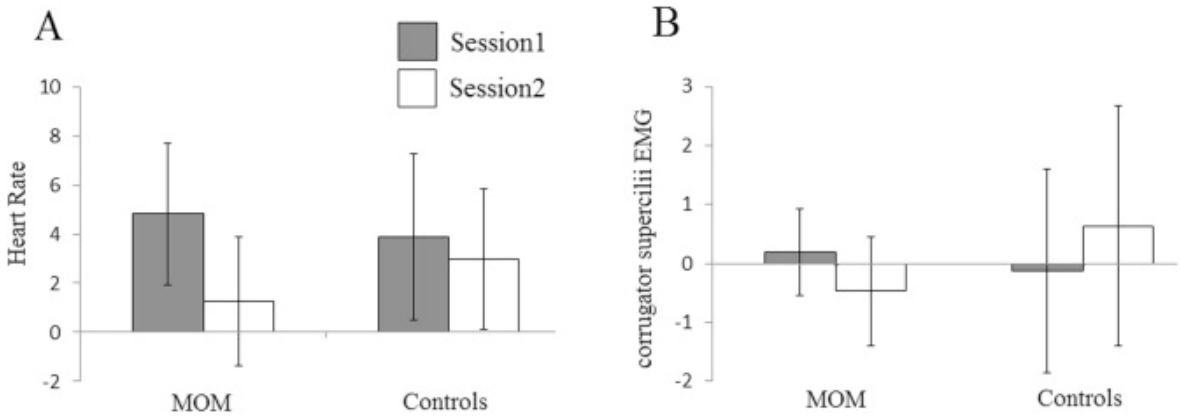

Figure 6. A) Change of heart rate with respect to baseline values in MOM and control participants for the two testing sessions (Session X Group interaction: $p < 0.05$); B) Change of corrugator supercilii muscle activity with respect to baseline values in MOM and control participants for the two testing sessions (Session X Group interaction: $p < 0.02$). Vertical bars denote standard deviations.