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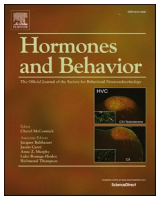

# Regulating intense fear: Does cognitive reappraisal attenuate physiological and subjective fear responses in an immersive VR environment?

Julian Packheiser [a,b,*], Dirk Scheele [a,b], Victoria Hube [a,b], Katja Langer [c], Oliver T. Wolf [c], Christopher Maymon [d], Sebastian Ocklenburg [e,f,g,1], Gesa Berretz [h,1]

[a] Department of Social Neuroscience, Center of Medical Psychology and Translational Neuroscience, Medical Faculty, Ruhr University Bochum, Bochum, Germany
[b] Research Center One Health Ruhr of the University Alliance Ruhr, Ruhr University Bochum, Germany
[c] Department of Cognitive Psychology, Institute of Cognitive Neuroscience, Faculty of Psychology, Ruhr University Bochum, Bochum, Germany
[d] School of Psychological Sciences, Victoria University of Wellington, Wellington, New Zealand
[e] Department of Psychology, MSH Medical School Hamburg, Hamburg, Germany
[f] Institute for Cognitive and Affective Neuroscience, MSH Medical School Hamburg, Hamburg, Germany
[g] Biopsychology, Institute of Cognitive Neuroscience, Faculty of Psychology, Ruhr University Bochum, Bochum, Germany
[h] Computational Neuroscience Lab, Donders Institute for Brain, Cognition and Behavior, Radboud University, the Netherlands

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ABSTRACT

Emotional experience and the regulation thereof are typically studied using picture inventories or short films to induce and modify affective states. These approaches, however, lack ecological validity due to their passive and receptive nature. Recent innovations in virtual reality and mobile neurophysiological technologies have enabled researchers to study the behavioral and neural correlates of more ecologically valid emotional responses. In this preregistered study, 58 healthy participants were randomly assigned to either use cognitive reappraisal (intervention) or to immerse themselves in their senses and surroundings (control) while walking across a wooden plank suspended 80 stories above the ground in virtual reality. We measured subjective fear ratings, salivary alpha amylase and cortisol levels, as well as frontal brain asymmetries, captured using mobile electroencephalography (EEG). Across both conditions, we found decisive evidence of increased subjective fear and salivary alpha amylase, a marker of sympathetic activation. However, we found no increase in cortisol levels following the task suggesting that subjective fear alone is not sufficient to trigger a cortisol response. In contrast to our hypotheses, the reappraisal group did not show any difference compared to the control group for neither emotional, endocrine nor neural measures. On the one hand, our findings may suggest that reappraisal might not be a suitable strategy to regulate realistic and intensely frightening situations. On the other hand, further analyses also indicated that the control group may have also regulated their emotions due to increased mindfulness of their inner states and their environment. Future studies are needed to confirm these observations and ascertain the efficacy of cognitive reappraisal on fear in realistic settings.

## 1. Introduction

In psychological and neuroscientific research, emotions are ubiquitously studied in laboratory settings by presenting images (e.g., pictures from the International Affective Picture System (IAPS), Lang et al., 2005) or emotional films (Courtney et al., 2010). While these methods can successfully manipulate emotional states (Detenber et al., 1998), they have low verisimilitude, requiring individuals to passively observe stimuli on a computer screen in a laboratory allowing only minimal behavioral engagement. However, action is a critical component of emotions (Güntürkün, 2019). Emotions motivate and prepare us to either *approach* (e.g., for emotions such as happiness, love or anger) or *withdraw* (e.g., fear, disgust or sadness, Harmon-Jones and Gable, 2018). As emotion perception and action tendencies are intricately connected, studying emotions primarily through passive perception may overlook important behavioral and neural dynamics, potentially limiting the

* Corresponding author at: Department of Social Neuroscience, Research Center One Health Ruhr of the University Alliance Ruhr, Medical Faculty, Universitätsstraße 150, 44801, Bochum, Germany.
*E-mail address:* julian.packheiser@rub.de (J. Packheiser).
[1] Shared senior authorship.

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generalizability of findings to real-world emotional experiences.

Recent advances in immersive technologies have made it possible to investigate emotional processing in more naturalistic environments. The application of virtual reality (VR) in laboratory settings has significantly facilitated studying emotions in realistic settings (Andreatta et al., 2023), thereby increasing ecological validity without sacrificing experimental control (Maymon et al., 2023). Moreover, the immersive nature of VR induces a sense of being *present* in the simulated environment, and much research has shown that presence plays a key role in eliciting emotional states (Baños et al., 2004; Marín-Morales et al., 2020; Maymon et al., 2024). For example, meta-analyses show that the use of Virtual Reality versions of the Trier Social Stress Test (VR-TSST) produces significant cortisol responses (Helminen et al., 2019). VR stress protocols that include public speaking or evaluation by a virtual audience elicit subjective anxiety and autonomic responses (e.g., heart rate, skin conductance) similar to real experimental conditions (Shiban et al., 2016). However, cortisol responses are often attenuated in VR compared to conventional methods. For studies targeting fear induction, such as heights, similar trends can be observed. For example, Martens et al. (2019) showed that VR height environments increased skin conductance, pulse and subjective stress and anxiety ratings, as well as altered heart rate variability. Although VR simulations are therefore feasible methods to induce negative affect, a prior study could not demonstrate that VR methodology evoked stronger emotional fear responses compared to the presentation via video clips (van der Wal et al., 2017). The use of VR is therefore not necessarily superior to classical methods of inducing affective states. Nonetheless, leveraging these innovative and interactive tools, researchers can safely and ethically expose participants to situations that feel genuinely threatening, leading participants to exhibit more realistic behavioral avoidance responses alongside robust increases in physiological arousal, e.g., skin conductance and heart rate (Kisker et al., 2021; Thomson et al., 2019).

In addition to permitting researchers to capture lifelike behavioral responses, research has found that more ecologically valid fear-induction paradigms more strongly manipulate subjective, physiological, and neural indices of fear responding. For example, in a recent experiment by El Basbasse et al. (2023), participants were exposed either to extreme heights in VR by walking across a wooden plank that was suspended high above a city street, or to a control condition in which the plank was presented as lying across the sidewalk on the street. Next, participants passively viewed IAPS images that were either fear-inducing or neutral. Fear ratings increased considerably when participants were on the plank, but only in the condition where the plank was suspended at height. Participants were not only able to explore the environment visually but were also required to move *from* a safe location (i.e., inside an elevator) *toward* an increasingly dangerous location. The authors found that fear ratings successively increased at high altitude when participants walked along the plank. Furthermore, frontal brain asymmetries as markers of emotional valence (Berretz and Packheiser, 2022; Sutton and Davidson, 2000) changed from standing in the elevator to standing at the end of plank. Specifically, right-hemispheric activation that is typically associated with negative emotional processing (Allen et al., 2018) increased with increasing fear ratings. Importantly, the experiment conducted by El Basbasse et al. (2023) compared neural activation patterns in VR with the presentation of IAPS pictures and could demonstrate that changes in frontal asymmetries were absent when observing fear-inducing IAPS pictures. Thus, contrasting observations by van der Wal et al. (2017), this study highlights that VR environments are potentially better suited to induce intense negative affect without jeopardizing ethical guidelines and the participants' well-being.

The determination of whether a stimulus is potentially threatening to an individual's well-being is subjective and depends on a process called appraisal (Lazarus and Folkman, 1984). During this evaluation, the available resources are compared to those necessary to cope with the stressor. If the available resources are deemed insufficient, the body and brain react with a typical stress response. The sympathetic adrenomedullary system as part of the autonomic nervous system releases epinephrine and norepinephrine leading to an increase in heart rate, blood flow to muscles and energy mobilization (Iversen et al., 2000). Activity of the Hypothalamus-Pituitary-Adrenocortical (HPA) axis starts with release of corticotropin-releasing hormone and arginine vasopressin from the hypothalamus leading to secretion of adrenocorticotropic hormone (ACTH) from the anterior pituitary into the blood stream. ACTH in turn causes the adrenal cortex to release cortisol (Stratakis and Chrousos, 1995). Typically, social-evaluative threat is used to induce HPA activation (Dickerson and Kemeny, 2004), but other paradigms without social-evaluative component, such as the cold pressor test and the aversive movie paradigm (Noack et al., 2019), also elicit increases in salivary cortisol as well. The latter uses passive viewing of a negative movie to induce negative affect and a cortisol response. When a situation is initially appraised as a stressor and a threat to the physical and psychological homeostasis due to insufficient resources, regulatory mechanisms are engaged (Gross, 2015). Emotion regulation refers to all deliberate or automatic attempts to change the duration, intensity or quality of an emotional state reflected in subjective, physiological or neural indices. Cognitive reappraisal comprises a well-studied emotion regulation strategy across clinical psychology, psychological science, and neuroscience. Cognitive reappraisal involves re-interpreting an initial emotional response to a stimulus or situation (Buhle et al., 2014). The reason for the high interest in cognitive reappraisal is due to its important role in clinical practice. Many neuropsychiatric disorders such as depression (Dryman and Heimberg, 2018) or PTSD (Aase et al., 2018) show deficits in emotion regulation and particularly in the ability to use cognitive reappraisal. These deficits not only manifest behaviorally but can be detected at the neural level as depression and PTSD patients show reduced dorsolateral prefrontal activation when using cognitive reappraisal (De la Peña-Arteaga et al., 2021; Rabinak et al., 2014).

A common denominator for most publications investigating the efficacy and mechanistic underpinnings of cognitive reappraisal is the use of pictures with negative valence to induce (and ultimately regulate) emotional states. In these scenarios, cognitive reappraisal has been shown to be highly successful as an emotion regulation strategy. However, the efficacy of reappraisal is not limited to situations in which the aversive stimulus is absent or only hypothetical. It has been demonstrated that emotional responses to the threat of acute, painful shocks can be downregulated using cognitive reappraisal (Yoshimura et al., 2014) illustrating that tangible aversive stimuli can be cognitively modulated. Another possibility to test the effects of reappraisal in emotionally intense scenarios is by exposing participants to simulated threats in VR. However, only a handful of studies have investigated the efficacy of cognitive reappraisal strategies in virtual environments. Combining VR with mobile EEG, Rodríguez et al. (2015) projected participants into a guided virtual park exploration that intended to induce sadness in the participants. Using source localization, the authors showed that participants in the reappraisal group showed stronger activation in the anterior cingulate cortex as well as the precuneus, both areas that have been demonstrated to be related to successfully applied reappraisal strategies (Buhle et al., 2014; Ferri et al., 2016; Wager et al., 2008). Reappraisal has also been investigated in a positive virtual environment where participants explored either a positive or neutral scene before being subjected to a stressful speech in front of an experimenter (Song et al., 2019). Participants in the reappraisal group showed higher positive affect in the neutral scene compared to a control group suggesting that the neutral environment was more positively evaluated and had stronger calming effects on the participants. Despite using a virtual environment, these studies, however, still were rather non-immersive as participants were passively observing their environment with no possibility to act upon the experienced emotions. Furthermore, none of these studies investigated whether an immediate fear-inducing stimulus of high emotional intensity can be effectively reappraised in a virtual environment. It therefore remains unclear if cognitive

reappraisal is a suitable strategy when directly confronted with an acute threat to one's well-being.

The present preregistered study aimed to investigate if cognitive reappraisal can be used to regulate situations in which naturalistic fear is immediate and visceral with the possibility to react to one's emotional state. Demonstrating that cognitive reappraisal is effective in these contexts highlights its translational potential as an intervention in everyday life, where it may help regulate physiological responses to panic-inducing situations or exposure to phobic stimuli. To this end, we employed the identical methodology that has been used in El Basbasse et al. (2023) combining mobile EEG with a virtual fear of heights paradigm (Ocklenburg and Peterburs, 2023). In this paradigm, participants could freely move along a wooden plank while either being at ground level or 80 stories in the air. Participants were randomly assigned to a cognitive reappraisal or control group. Participants in the reappraisal group were instructed to cognitively re-evaluate the height situation in a more positive manner while participants in the control group were instructed to simply focus on their senses and inner states. In addition to measures of subjective fear ratings and frontal brain asymmetries which have been robustly demonstrated to be linked to emotional processing of both positive and negative affect across laboratory and naturalistic tasks alike (Berretz et al., 2022a; Harmon-Jones and Allen, 1998), we also hypothesized that salivary cortisol as marker of acute stress would be increased in response to realistic fear. Increases in cortisol reflect HPA axis activation which is typically activated during psychosocial stress (Eckstein et al., 2014; James et al., 2023). While most studies show that social evaluative threat (e.g., being judged by others on your performance) results in the secretion of cortisol, stimuli or activities without a socially-evaluative component such as parachute jumping (Deinzer et al., 1997), electric shocks (Vachon-Presseau et al., 2013) or fear-inducing cues (e.g., Alpers et al., 2003) have also resulted in increases in cortisol secretion in past studies. Because it remains an open question which conditions induce a cortisol stress response, the present study includes a measure of cortisol as a hormonal marker. In accordance with our preregistration, we formulated the following preregistered hypotheses:

(1) Individuals undergoing the cognitive reappraisal intervention will show reduced fear ratings during the paradigm and less negative affect after the paradigm compared to the control group.
(2) Frontal right-hemispheric activation (indicative of negative affect processing) will be lower in the cognitive reappraisal group compared to the control group during the paradigm.
(3) a) Cortisol release will be increased following the fear of heights paradigm in both the reappraisal and control group.
    b) Individuals in the cognitive reappraisal group will show lower levels of cortisol release compared to the control group.

Exploratorily, we also collected data on salivary alpha amylase (sAA) as sAA increases supposedly reflect activation of the sympathetic adrenal medullar (SAM) system (van Stegeren et al., 2008). This system is typically recruited in response to stressful activities such as parachute jumps (Chatterton et al., 1997) but also following watching aversive pictures (Sánchez-Navarro et al., 2012). In line with our hypothesis regarding cortisol, we expected a general sAA response due to fear exposure but a regulating effect of the reappraisal intervention.

## 2. Methods

### 2.1. Preregistration

The study was preregistered at the Open Science Framework under the following link: https://osf.io/knj32.

### 2.2. Participants

The study aimed to collect data from 62 participants to detect a medium effect size of $d = 0.6$ with 80% power as calculated using G*power (Faul et al., 2007) in a 2 × 3 mixed ANOVA design. The effect size was chosen in accordance with both medium-to-large effect sizes in changes of frontal alpha asymmetries reported by El Basbasse et al. (2023) and a large effect in a behavioral study investigating effect sizes of cognitive reappraisal (Langeslag and Surti, 2017). Participants below 18 years and above 35 years of age, with a current diagnosis of neurodevelopmental, endocrine, psychiatric, or neurological disorders, extreme fear of heights (measured via an acrophobia questionnaire, Hüweler et al., 2009) or doing shift work were excluded. Furthermore, we excluded individuals who smoke regularly and with high BMI (>27) as these factors are known to influence salivary cortisol levels (Badrick et al., 2007; Björntorp and Rosmond, 2000). Finally, participants had to have normal or corrected-to-normal vision and speak German fluently due to the questionnaires and reappraisal/control instructions being in German. Due to technical issues with the EEG recording systems ($n = 2$) and participants aborting the experiments (n = 2), the final sample included in the data analysis comprised 58 individuals ($n = 39$ or 67% female, mean age = 24.0 years). The final sample was demographically comparable to the pre-study by El Basbasse et al. (2023, 62% female, mean age = 24 years). A sensitivity analysis revealed that this sample could detect effect sizes of d = 0.61 with 80% power in a 2 × 3 mixed ANOVA design as outlined in the preregistration illustrating that medium to large effects sizes could still be detected reliably using this sample size. The study was accepted by the ethics committee of the Faculty of Psychology at Ruhr-University Bochum (application #915). All participants gave their written informed consent at the beginning of the experiment. Participants received monetary compensation or course credit for their participation. The experiment was conducted in accordance with the Declaration of Helsinki.

### 2.3. Experimental protocol and materials

All experimental sessions took place between 1 p.m. and 6 p.m. to control for circadian cortisol fluctuations (Chan and Debono, 2010; Schneider et al., 2023). Upon arrival at the laboratory, participants were first informed about the nature of the task in both written and oral form before providing written consent to participate. Immediately after, participants provided a saliva sample as a baseline measure of cortisol as marker of HPA-axis activity (Törnhage, 2009) and sAA, a marker of sympathetic nervous activity (Nater and Rohleder, 2009). Additionally, participants filled out the German version of the Positive And Negative Affect Schedule (PANAS, Krohne et al., 1996) as a record of their baseline emotional state. Participants were then instructed to fill out a worksheet containing information about either cognitive reappraisal in the experimental group or the human senses in the control group (see Supplementary material for an English translation of the worksheets). In the reappraisal group, participants had to re-iterate the information they had read and provide examples of how they could apply cognitive reappraisal to hypothetical example situations (see Supplementary material for details). They were then asked specifically about situations involving fear of heights and were instructed to develop a personalized reappraisal strategy to help regulate their emotions when placed in such scenarios. The personalized reappraisal strategy was shortly discussed with the experimenter to ensure that the concept of reappraisal was understood correctly. In the control group, participants also had to summarize the given information and provide information about their personal experience of fearful situations but also responded to questions about previous situations in which they were confronted with heights. The control worksheet was designed to take the same amount of time as the reappraisal worksheet while recruiting comparable cognitive resources. Importantly, participants in the control group were instructed to perceive the VR situation as naturally as possible and to focus on their

sensory experiences while in the simulation. Participants were randomly assigned to the experimental or control group. In the final sample included for analysis, 31 participants took part in the reappraisal condition and 27 participants took part in the control condition.

After the participants completed filling out the worksheets, participants were equipped with the mobile EEG cap (LiveAmp 32, Brain Products GmbH, Gilching, Germany) comprising a 32 electrodes system arranged in line with the international 10–20 system (Morley et al., 2016). The ground electrode was located at FPz and the reference electrode at FCz. In addition to the 32-electrode channels, three acceleration sensors implemented in the wireless amplifier recorded measures of head and body movements along the *X*-, *Y*- and *Z*-axes. A wireless amplifier located on the back of the head amplified the recorded signal and transmitted it to the recording software (Brain Vision Recorder) on a laptop with a sampling rate of 1000 Hz. The impedance cut-off was set to less than 5 kΩ for an adequate EEG signal. To fit the HTC Vive head-mounted display (HMD) that was used to present the VR environment, several EEG caps in different sizes were adjusted for VR-compatible use by MES Forschungssysteme GmbH (https://mes.gmbh/). A visual representation of the setup is provided in El Basbasse et al. (2023).

The VR task was presented using the HTC Vive HMD with corresponding hand controllers (https://www.vive.com/us/). The HMD comprises an inbuilt high-resolution display (2160 × 1200 pixel) with a 110° field of view at a refresh rate of 90 Hz. In addition, it contains accelerometers and a gyroscope to detect omnidirectional movement and adjustable lenses. The VR environment was created in the laboratory using the Unity game engine (https://unity.com/). The simulation was projected to the HMD using the SteamVR runtime application. The physical measurements of the virtual room were approximately 5 × 6 m. The VR set-up included two base stations (height: *ca* 2.4 m, distance between the base stations: *ca* 3 m) framing the virtual room, the HMD, two controllers and one laptop with an external number pad to choose VR conditions. The controllers represented the participants' hands while in the virtual environment. Two laptops were used to record the EEG signal and to run the VR paradigm.

Before starting the VR simulation, participants were instructed that they would first walk a wooden plank at ground level (ground condition) and then walk it atop of a skyscraper environment (height condition). Upon starting the VR set-up, participants were projected into a virtual city environment. The participants started at ground level afoot of a tall skyscraper inside its elevator. Participants were asked to slowly move outside the elevator to explore the street. After a short exploration period, the participants were asked to turn around and re-enter the elevator. Once inside, participants used their right hand to press a button inside the elevator, causing the elevator doors to close. While the participant was in the elevator, the experimenter moved a real wooden plank in front of the feet of the participants that they needed to walk on to increase the realistic experience of the scenario. The elevator then shortly moved upwards but returned to the ground floor to start the ground condition. The elevator door then re-opened starting the ground condition with the wooden plank being projected into the virtual environment (matching the physical plank in the experimental room). Here, participants were instructed to remain for 1 min inside the elevator and explore the environment visually (elevator segment, see Fig. 1A for a view from the participant's perspective). Upon completion, participants had to rate their fear level as well as their sense of presence in the virtual world on a scale from 1 to 10 (ranging from no fear or presence to a very high sense of fear or presence). The ratings were orally asked for by the experimenter and not presented within the simulation to maintain the sense of presence in VR. After the rating, they were asked to take one step onto the plank and again visually explore for 1 min (start of plank segment, Fig. 1B) and give another rating. Finally, they were told to walk to the end of the plank and once more explore their environment visually followed by providing fear and presence ratings (see Fig. 2A–C for a representation of the experimental task from the experimenter's point of view). After the ground condition was completed, participants were told to turn around and re-enter the elevator. Before pressing the button, participants were reminded to use either the cognitive reappraisal strategy (reappraisal group) or experience the situation naturally while focusing on their sensory experiences (control group) once the height condition has started. After this clarification, they pressed the button and the elevator moved upwards but continued upwards to arrive high up in the air. The experimental protocol was identical to that of the ground condition starting in the elevator (Fig. 1C) and ending at the end of the plank (Fig. 1D). Following the height condition, participants could

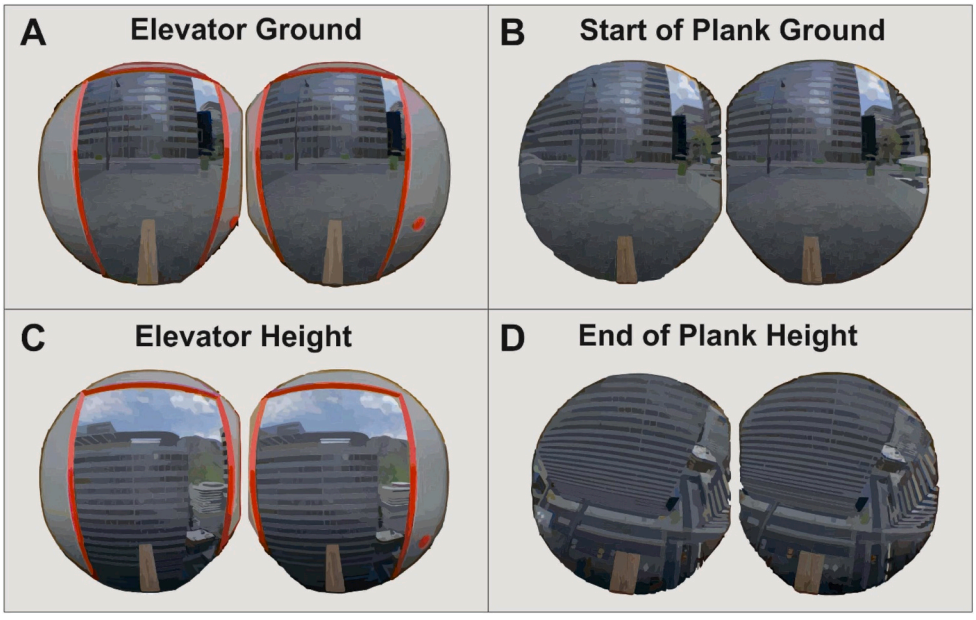


**Fig. 1.** Perspective through the VR goggles in different experimental conditions. A) View of the participant while standing in the elevator during the ground condition. B) Same as in A), but for the start of plank segment. C) Same as in A), but for the height condition. D) Downward view of the participant during the end of plank segment in the height condition.
Figure adapted from El Basbasse et al. (2023) under a CC-BY-4.0 license for unrestricted use.

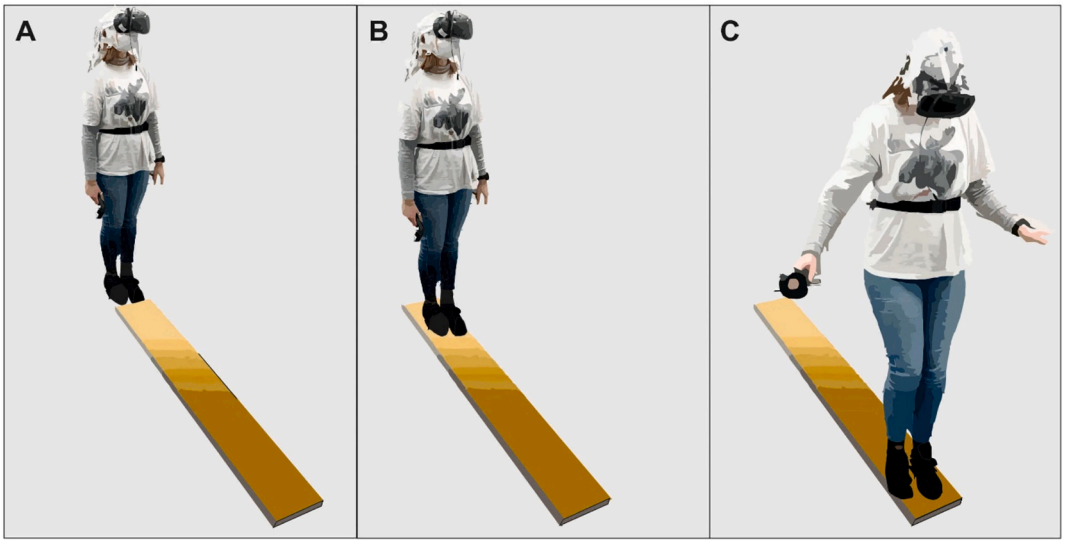


**Fig. 2.** View of the experimenter monitoring the participant during the elevator (A), start of plank (B) and end of plank segment (C). Figure adapted from El Basbasse et al. (2023) under a CC-BY-4.0 license for unrestricted use.

remove the HMD with the help of the experimenter. The total duration of the VR task was around 20 min.

Immediately after the VR simulation had concluded, participants were asked to once again fill out the PANAS questionnaire and provide another saliva sample. Afterwards, participants were helped with the removal of the EEG cap and could wash their hair. The participants then returned to the experimental room to fill out several questionnaires. First, they provided information about the unpleasantness and stressfulness of the task and how well they could implement the instructions (cognitive reappraisal in the experimental group and sensory focus in the control group). These questions were answered on a visual analogue scale ranging from 0 (not at all) to 100 (very). They then filled out the Simulator Sickness Questionnaire (SSQ, (Kennedy et al., 1993)) and the iGroup Presence Questionnaire (IPQ, (Regenbrecht et al., 1998)). These questionnaires evaluate the sense of immersion and how it affected participants in the VR simulation. The SSQ evaluates on a 4-point Likert scale (from 'not at all' to 'strongly') to what degree participants experienced 16 symptoms characteristic for simulations in VR, e.g. blurred vision, dizziness (with eyes open or closed) or general discomfort. The IPQ assesses how present participants felt in the virtual environment and if a sense of 'being there' could be induced. In addition, participants provided further saliva sample 15-, 30- and 45-min post conclusion of the VR experiment. A full overview of the procedure is depicted in Fig. 3.

### 2.4. Physiological measurements

Saliva analyses were conducted in the in-house laboratory of the Departments of Genetic Psychology and Cognitive Psychology at the Ruhr University Bochum. Saliva was analyzed using a cortisol enzyme-linked immunosorbent assay (Cortisol Saliva ELISA, IBL, Hamburg, Germany) with intra-assay coefficients of variance (CV) below 5% and inter-assay CVs below 15%. In addition, the enzyme alpha-amylase was analyzed from the saliva samples. A colorimetric test using 2-chloro-4-nitrophenyl-α-maltrotriosoide (CNP-G3) as a substrate reagent was applied to measure sAA concentration (Lorentz et al., 1999). Intra- and inter-assay variabilities were below 10%.

### 2.5. EEG preprocessing

EEG data was preprocessed using the program BrainVision Analyzer (Brain Products GmbH, Gilching, Germany) following the protocol of El Basbasse et al. (2023). The data was first downsampled from 1000 to 250 Hz to shorten processing time. A 0.5 Hz high-pass filter (zero phase shift Butterworth filter, time constant 0.3183099) was applied to avoid interference from non-physiological high-frequency sources. A 50 Hz notch filter was used to exclude electrical noise from surrounding devices. After a visual raw data inspection during which artifacts from heavy movements were manually excluded, an InfoMax algorithm independent component analysis (ICA) extracted artifacts caused by blinks

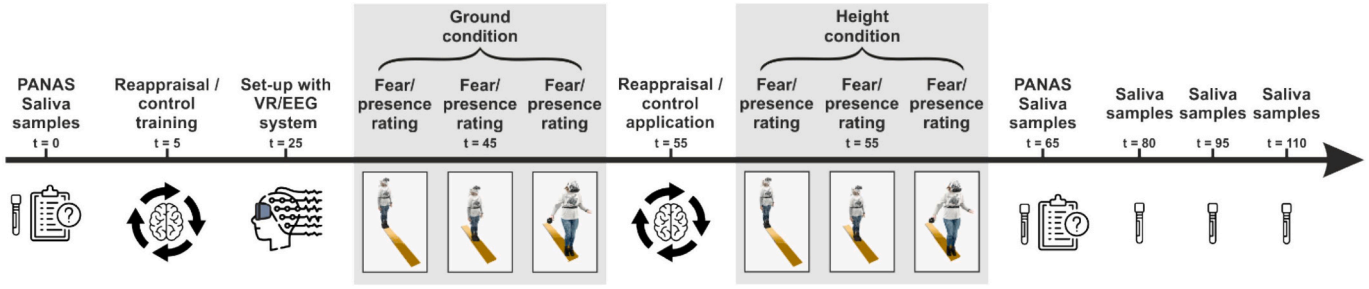


**Fig. 3.** Timeline of the experimental procedure. After providing an initial saliva sample and ratings on their affective states, participants received training material to familiarize themselves with cognitive reappraisal or the work sheet on human senses. Subsequently, participants were equipped with the VR and EEG system and were projected in the VR simulation to start the ground condition. The participants were then instructed to use the reappraisal strategy or focus on their senses before undergoing the height condition. Following the VR procedure, participants provided another affect rating and saliva samples. The onset of each procedural step relative to study begin is indicated by t (in minutes).

and horizontal eye movements as well as pulse artifacts. Flat line channels or channels with poor recording quality were then interpolated using data from surrounding electrodes. In addition, the reference electrode FCz was interpolated and the data was re-referenced to the average signal of all electrodes to reduce the impact of volume conduction. After re-referencing, a second filter was applied with a low cut-off at 1 Hz and a high cut-off at 45 Hz. The individual task elements (i.e., elevator, start of plank, end of plank) were subdivided into segments of 60 s. In a second step, these segments were further segmented into 60 equally long 1 s segments. A fast Fourier transformation (Hanning window of 10%) was applied to extract alpha oscillations (8–12 Hz) from the signal. Lastly, the average power was calculated for each recording segment in the ground and height condition for the F3, F4, F7 and F8 electrodes in accordance with our preregistered analyses. As we were specifically interested in hemispheric asymmetries, we calculated asymmetry indices (AIs) by subtracting the natural logarithm of the power in the left hemisphere from the natural logarithm of the power in the right hemisphere (Reznik and Allen, 2018).

$$AI = \ln(power\ right) - \ln(power\ left)$$

Data from the movement accelerometers were not further investigated as they had no impact on the results observed in El Basbasse et al. (2023).

### 2.6. Statistical analyses

#### 2.6.1. Confirmatory analyses

As outlined in our preregistration, data analysis was conducted using frequentist statistics and complemented by Bayesian statistics to obtain Bayes Factors (BF) that can provide evidence in favor of the null hypothesis. The $BF_{incl}$ is used for the results of ANOVAs and the $BF_{10}$ is used for relevant *post-hoc* tests. The BF represents the amount of evidence for the null or alternative. For example, a $BF_{incl}$ or $BF_{10}$ of 2 indicates that there is twice as much evidence for the alternative compared to the null hypothesis whereas a $BF_{incl}$ or $BF_{10}$ of 0.5 indicates twice as much evidence for the null compared to the alternative hypothesis. While BFs provide continuous measures of evidence, moderate evidence for the alternative hypothesis has been suggested to be observed at values $> 3$, and moderate evidence for the null hypothesis is observed at values $<$ 0.33 (Lee and Wagenmakers, 2014). Values between values of 3 and 0.33 are considered anecdotal whereas values $> 10$ or below 0.1 reflect strong evidence for the H1 and H0, respectively. We used the default priors used in JASP for Bayesian analyses. All analyses were performed in R (version 4.3.3.) and JASP (version 0.18.1.0).

Confirmatory analyses were performed for the heights condition specifically as the intervention was targeted at this condition in accordance with our preregistration. To test the first hypothesis, fear ratings were tested in a 2 × 3 repeated-measures ANOVA with the within-participant factor *time point* (levels: elevator, start of plank, end of plank) and the between-participant factor *intervention* (levels: reappraisal, control). For positive and negative affect ratings measured via the PANAS, the within-participant factor *time point* only had two levels (i.e., pre-task, post-task). To test our second hypothesis, the analysis plan followed the identical protocol as for the fear ratings (2 × 3 repeated-measures ANOVA with the within-participant factor *time point* and the between-participants factor *intervention*). EEG data were analyzed separately for the F3/F4 and F7/F8 electrode pairs in accordance with our preregistration. Changes in cortisol levels (hypothesis 3a and 3b) were measured using a 2 × 5 repeated measures ANOVA with the within-participant factor *time point* (levels: baseline, immediately post-task, 15 min post-task, 30 min post-task and 45 min post-task) and the between-participants factor *intervention* (levels: reappraisal, control). Note that we deviated from the preregistration, which specified only four measurement time points, by adding a fifth measurement taken 45 min post-task to improve measurement sensitivity for exploratory area under the curve (AUC) analyses (Pruessner et al., 2003). Cortisol levels were log-transformed due to skewedness. This transformation resulted in a normal distribution of cortisol levels. ANOVAs were Greenhouse-Geisser corrected in case of violated sphericity. All post hoc tests were Bonferroni corrected.

#### 2.6.2. Exploratory analyses

In addition to comparing fear ratings across time points in the experiment, we also ascertained if presence ratings changed over time using the same analysis as described for the fear ratings. For cortisol, we also computed the AUC with respect to increase (AUCi) using the formula by Pruessner et al. (2003). Furthermore, we tested if sAA levels increased in response to the VR paradigm in dependence of the intervention. The analysis followed the same protocol as the cortisol analysis. AUC analyses were however not performed due to the short response profile of sAA (Het et al., 2020). Using independent sample *t*-tests, we additionally compared the experimental and control groups on their self-reported assessments of unpleasantness, stressfulness, and success in following the instructions given for the reappraisal and control group. Subjective ratings of fear were correlated with frontal AIs across both experimental groups to identify if individual differences in task experience are associated with neural processing. All analyses that were carried out as preregistered for the height condition were exploratorily investigated for the ground condition as well. To disentangle whether differences emerged due to the change from ground to height condition rather than VR exposure alone, we conducted exploratory comparisons between the height and ground condition using a 2 × 2 × 3 ANOVA design with the factors *time point*, *intervention* as well as *condition* (levels: ground, height).

## 3. Results

### 3.1. Subjective ratings

To identify if fear ratings differed across time points during the task and differentially between the intervention groups, a 2 × 3 repeated measures ANOVA with the factors *time point* and *intervention* was performed. For the ground condition, there was a main effect of *time point* ($F_{(2,112)} = 3.99$, $p = .021$, $\eta_p^2 = 0.01$, Fig. 4A). Evidence for this effect was, however, only anecdotal ($BF_{10} = 1.59$). Fear ratings slightly increased from the elevator to the start of plank ($t = 2.59$, $p = .033$, $BF_{10} = 2.98$). There was no interaction effect ($F_{(2,112)} = 1.26$, $p = .288$, $\eta_p^2 = 0.004$, $BF_{10} = 0.23$). Fear ratings in the height condition showed a significant main effect of *time point* ($F_{(1.567,87.768)} = 45.71$, $p < .001$, $\eta_p^2 = 0.45$, Fig. 4B). The evidence for this effect was decisive ($BF_{10} > 100$). Post hoc tests revealed that fear increased from the elevator to the start of plank segment ($t = 4.43$, $p < .001$, $BF_{10} > 100$) as well as end of plank segment ($t = 9.55$, $p < .001$, $BF_{10} > 100$). In addition, fear ratings increased from the start of plank to the end of plank segment ($t = 5.12$, $p < .001$, $BF_{10} > 100$). However, no interaction effect with the experimental intervention was observed ($F_{(1.567,87.768)} = 0.73$, $p = .452$, $\eta_p^2 = 0.01$). There was moderate evidence against an interaction effect ($BF_{10} = 0.23$). The exploratory 2 × 2 × 3 ANOVA including the factor *condition* revealed a significant main effect of *condition* ($F_{(1,56)} = 196.49$, $p < .001$, $\eta_p^2 = 0.78$, $BF_{10} > 100$) and significant interaction between *condition* and *time point* ($F_{(1.575,88.179)} = 29.90$, $p < .001$, $\eta_p^2 = 0.35$, $BF_{10} > 100$) with higher fear ratings in the height condition for all three time points (all *p*s $< .001$, $BF_{10}$s $> 100$).

The same analysis was conducted for presence ratings. In the ground condition, there was anecdotal evidence for a main effect of *time point* ($F_{(1.650,90.749)} = 4.01$, $p = .028$, $\eta_p^2 = 0.07$, $BF_{10} = 1.14$, Fig. 4C) with presence ratings slightly increasing from the elevator to the start of plank segment ($t = 2.73$, $p = .022$, $BF_{10} = 3.58$). No interaction was observed ($F_{(1.650,90.749)} = 0.53$, $p = .554$, $\eta_p^2 = 0.01$, $BF_{10} = 0.07$). In contrast to fear ratings, presence ratings in the height condition showed neither a main effect of *time point* ($F_{(1.604,88.231)} = 3.13$, $p = .059$, $\eta_p^2 = 0.009$, $BF_{10} = 0.58$, Fig. 4D) nor an interaction effect with the

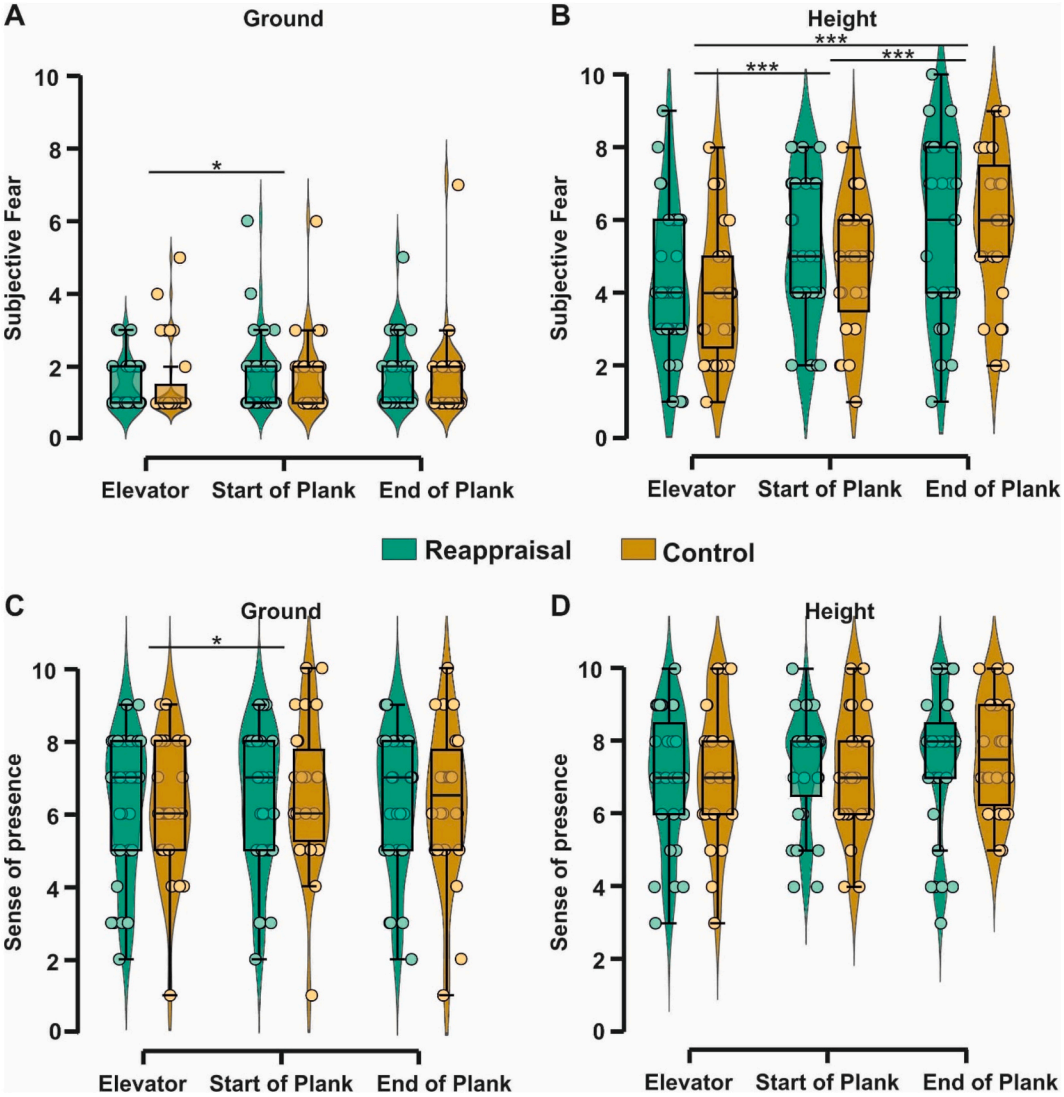


**Fig. 4.** Top: Subjective fear ratings for the ground (A) and height (B) condition for all recording segments across the experimental groups (reappraisal, control). Bottom: Presence ratings for the ground (C) and height (D) condition for all recording segments across the experimental groups (reappraisal, control). Bars above the boxplots mark significant post hoc effects between the recording segments across experimental groups. Boxplots reflect the median, the first and third quartile, and the interquartile range. *$p < .05$, ***$p < .001$.

experimental intervention ($F_{(1.604,88.231)} = 0.36$, $p = .654$, $\eta_p^2 = 0.001$, $BF_{10} = 0.08$). The exploratory 2 × 2×3 ANOVA including the factor *condition* revealed significantly higher presence ratings in the height compared to ground condition ($F_{(1,56)} = 26.60$, $p < .001$, $\eta_p^2 = 0.33$, $BF_{10} > 100$).

For positive and negative affect, a 2 × 2 repeated-measures ANOVA was conducted as it was only measured pre- and post-task. There was a main effect of *time point* for the positive affect measure ($F_{(1,55)} = 34.92$, $p < .001$, $\eta_p^2 = 0.39$) with decisive evidence for an effect ($BF_{10} > 100$). Positive affect increased significantly from the pre- to post-task measurement (see Fig. 5A). No interaction with the experimental intervention was observed ($F_{(1,55)} = 0.23$, $p = .635$, $\eta_p^2 = 0.004$, $BF_{10} = 0.29$). For negative affect, a main effect of *time point* was detected as well ($F_{(1,55)} = 4.34$, $p = .042$, $\eta_p^2 = 0.07$) with negative affect increasing slightly from the pre- to post-task measurement (see Fig. 5B). Evidence for this effect was however only anecdotal ($BF_{10} = 1.40$). Again, there was no interaction effect between *time point* and experimental intervention ($F_{(1,55)} = 0.26$, $p = .614$, $\eta_p^2 = 0.005$, $BF_{10} = 0.17$).

Subjective stress and unpleasantness ratings were compared between the intervention groups using independent sample *t*-tests to determine if the reappraisal intervention resulted in a reduction thereof. We could not observe any significant differences between the experimental and control group ($t_{(56)} = 0.62$, $p = .536$, $BF_{10} = 0.31$; $t_{(56)} = 0.60$, $p = .550$, $BF_{10} = 0.31$, respectively). We also compared success ratings to assess whether the reappraisal strategy could be implemented as well as the control instruction. Experienced success in following the instructions did not differ between the groups either ($t_{(56)} = 1.10$, $p = .275$, $BF_{10} = 0.44$) suggesting that participants could likely apply the reappraisal strategy and naturally focus on their sensory experiences. Descriptive statistics for all subjective ratings can be found in Supplementary Tables 1–7.

### 3.2. EEG data

To determine if frontal asymmetries changed over time and differentially between the groups, a 2 × 3 repeated-measures ANOVA was conducted. In the ground condition, there was neither a main effect of *time point* nor an interaction with the experimental intervention (main effect: $F_{(2,112)} = 1.08$, $p = .344$, $\eta_p^2 = 0.02$, $BF_{10} = 0.14$; interaction: $F_{(2,112)} = 2.34$, $p = .101$, $\eta_p^2 = 0.04$, $BF_{10} = 0.10$, Fig. 6A). Frontal asymmetries measured during the height condition across the F3/F4 sites did not demonstrate any main effect of *time point* ($F_{(2,112)} = 0.26$, $p = .774$, $\eta_p^2 = 0.005$, $BF_{10} = 0.05$) nor any interaction with the

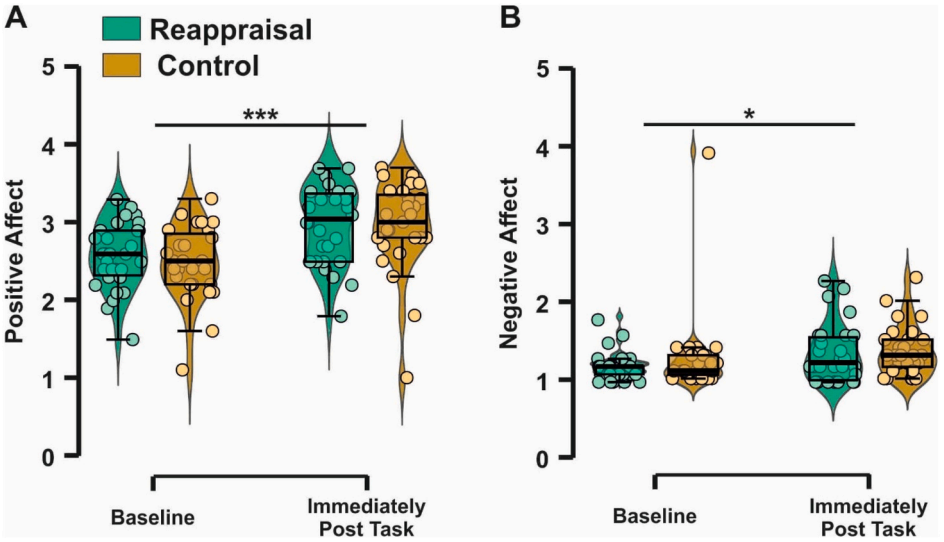


**Fig. 5.** Positive (A) and negative affect rating (B) for both experimental groups (reappraisal, control) before and after the VR task. Bars above the boxplots mark significant post hoc effects between the measurements across experimental groups. Boxplots reflect the median, the first and third quartile, and the interquartile range. *$p < .05$, ***$p < .001$.

experimental intervention ($F_{(2,112)} = 1.21$, $p = .302$, $\eta_p^2 = 0.01$, $BF_{10} = 0.02$, Fig. 6B). The exploratory 2 × 2 × 3 ANOVA including the factor condition did not reveal any significant differences between the height and ground condition ($F_{(1,56)} = 0.15$, $p = .705$, $\eta_p^2 = 0.00$, $BF_{10} = 0.06$).

For the F7/F8 electrode pair during the ground condition, neither a main effect of *time point* ($F_{(1.789,100.189)} = 1.51$, $p = .228$, $\eta_p^2 = 0.03$, $BF_{10} = 0.17$) nor an interaction effect between *time point* and experimental intervention ($F_{(1.789,100.189)} = 0.65$, $p = .507$, $\eta_p^2 = 0.01$, $BF_{10} = 0.08$) were observed (Fig. 6C). In the heights condition, we could not detect any change in frontal alpha asymmetry across time points ($F_{(2,112)} = 0.40$, $p = .673$, $\eta_p^2 = 0.007$, $BF_{10} = 0.06$) and there was no interaction effect either ($F_{(2,112)} = 0.26$, $p = .775$, $\eta_p^2 = 0.005$, $BF_{10} = 0.01$, Fig. 6D). Descriptive statistics for the AI analyses can be found in Supplementary Tables 8–11. The exploratory 2 × 2 × 3 ANOVA including the factor condition did not reveal any significant differences between the height and ground condition ($F_{(1,56)} = 0.43$, $p = .514$, $\eta_p^2 = 0.01$, $BF_{10} = 0.09$).

To identify if fear ratings were associated with neural processing, we also ran correlational analyses for both the height and ground condition between the fear ratings and frontal AIs. Due to the exploratory nature of the analysis, we used a Bonferroni-corrected threshold of $p = .05/12$ or .0042, as each fear rating from each time point (elevator, start of plank, end of plank) was correlated with the respective AI from two electrode pairs (F3/F4, F7/F8) for both the height and ground condition. No correlations reached significance (all $ps > .056$, all $BFs < 0.97$).

### 3.3. Biomarkers of stress reactivity

As cortisol was measured at five different time points, a 2 × 5 repeated-measures ANOVA was run. The analysis revealed decisive evidence for a main effect of *time point* ($F_{(1.904,\ 102.840)} = 59.92$, $p < .001$, $\eta_p^2 = 0.53$, $BF_{10} > 100$, Fig. 7A). In contrast to our hypothesis, however, cortisol did not show an increase following the fear of heights paradigm. Rather, cortisol levels significantly dropped from baseline to any other time point of measurement ($ts > 9.62$, $ps < .001$, Fig. 6A). There was no interaction effect with the experimental intervention ($F_{(1.904,\ 102.840)} = 1.66$, $p = .197$, $\eta_p^2 = 0.03$, $BF_{10} = 0.48$). Comparing AUCi between the experimental and control group did not reveal a significant difference either ($t_{(54)} = 0.93$, $p = .358$, $d = 0.25$, $BF_{10} = 0.39$).

For sAA levels, the exploratory analysis followed the same principle as for cortisol. We observed a main effect of *time point* ($F_{(3.200,\ 172.790)} = 19.29$, $p < .001$, $\eta_p^2 = 0.26$, Fig. 7B) with decisive evidence for the alternative hypothesis ($BF_{10} > 100$). Post hoc tests revealed that sAA levels significantly increased from baseline to the post-task measurement ($t = 4.02$, $p < .001$, $BF_{10} = 62.38$) but also decreased from baseline to the fourth measurement ($t = 2.86$, $p = .047$, $BF_{10} = 2.52$). There was furthermore a drop in sAA levels from the second to the fourth ($t = 6.88$, $p < .001$, $BF_{10} > 100$) and fifth measurement ($t = 6.62$, $p < .001$, $BF_{10} > 100$). Finally, sAA levels decreased from the third to the fourth ($t = 5.66$, $p < .001$, $BF_{10} > 100$) and fifth measurement ($t = 5.40$, $p < .001$, $BF_{10} = 80.04$). No interaction was observed between *time point* and the experimental intervention ($F_{(3.200,\ 172.790)} = 1.10$, $p = .354$, $\eta_p^2 = 0.02$, $BF_{10} = 0.19$). Descriptive statistics for cortisol and sAA can be found in Supplementary Tables 12 and 13.

## 4. Discussion

In this study, we investigated if the exposure to a height scenario using VR results in increased subjective fear and changes in neural markers of affective processing as measured by frontal alpha asymmetry. We also investigated if being subjected to this fear of heights paradigm results in HPA-axis or sympathetic nervous system responses. Importantly, we assessed whether a cognitive reappraisal intervention can be used to regulate emotional, neural and endocrine responses to the realistic virtual environment. For subjective fear ratings, we could replicate the findings of the pre-study (El Basbasse et al., 2023) as we could show that the plank paradigm successfully induced subjective fear. Task exposure also resulted in increases in sAA but there was no increase in cortisol due to the fearful situation. At the neural level, we could not replicate the changes in frontal asymmetry observed in El Basbasse et al. (2023). With respect to the reappraisal intervention, participants instructed to use cognitive reappraisal did not report differences in subjective fear, sAA, cortisol or lateralized frontal alpha activity relative to controls.

In contrast to our hypothesis, we could not confirm that individuals in the reappraisal group downregulated their fear responses in the VR simulation more than those in the control group. This lack of modulation was not due to floor effects as the task was successful in eliciting emotional fear responses. The non-significant findings between groups were further supported by Bayes factors that provided overall moderate to strong evidence for the absence of an effect suggesting that there was no difference between the reappraisal and the control group. Because reappraisal has been shown to be a successful regulation strategy even in

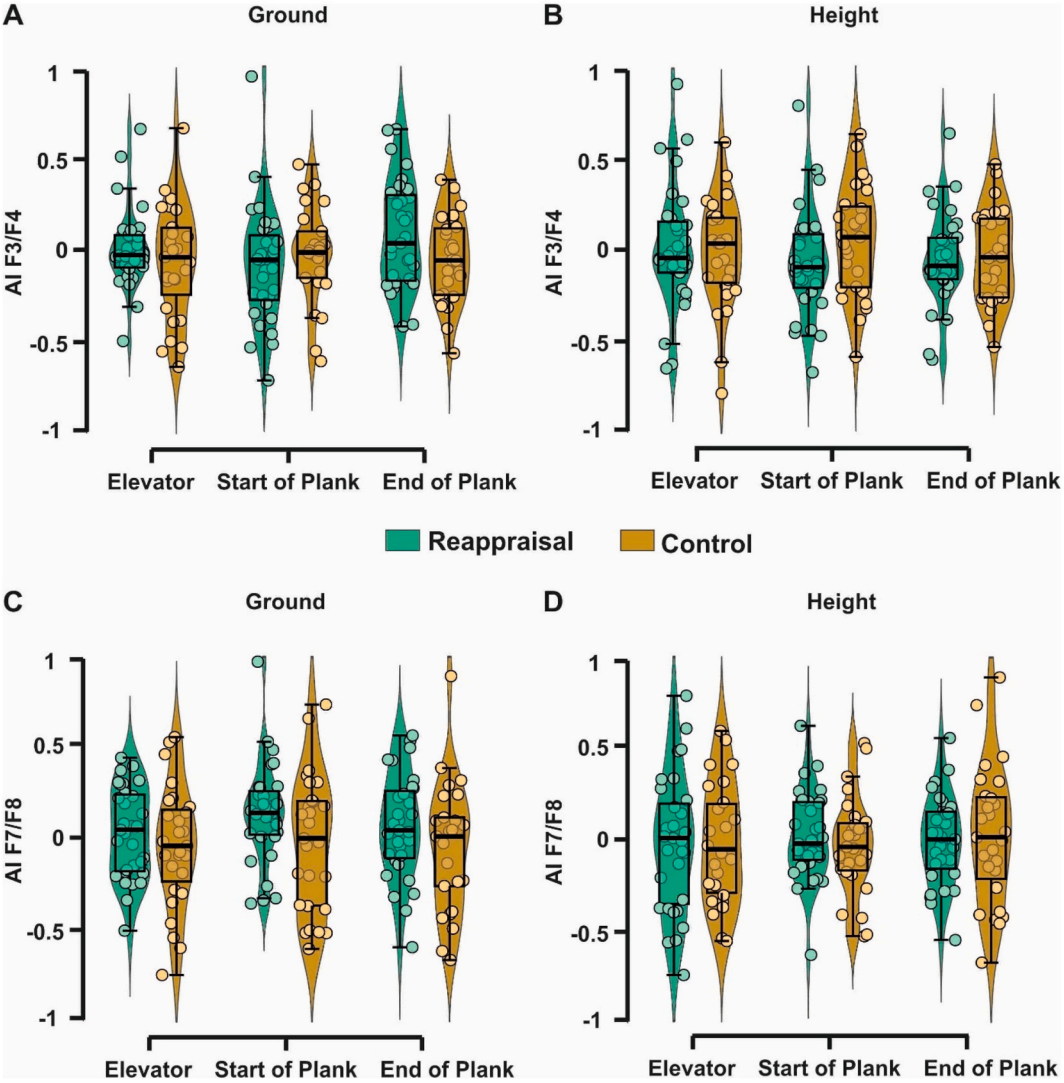


**Fig. 6.** Top: AI scores at the F3/F4 electrode site for the ground (A) and height (B) condition for all recording segments across the experimental groups (reappraisal, control). Bottom: AI scores at the F7/F8 electrode site for the ground (C) and height (D) condition for all recording segments across the experimental groups (reappraisal, control). Boxplots reflect the median, the first and third quartile, and the interquartile range.

the face of physical threats (albeit to a lower degree compared to distraction strategies, Adamczyk et al., 2023), it begs the question why the reappraisal intervention did not work in this particular paradigm to downregulate the emotional response.

One potential explanation could relate to the fact that our emotional stimulus was of high intensity, as illustrated by high fear ratings as well as participants who terminated the experimental session due to fear to walk the plank in the simulation. As outlined by Milyavsky et al. (2019), emotional intensity is a key driving force of emotion regulation as stimuli that cause strong affective responses require regulatory processes to achieve a stable state of emotional equilibrium and balance. However, intensity functions simultaneously as a restraining force as an emotionally intensive situation requires a lot of cognitive resources and is considerably more difficult to reappraise compared to an emotionally weak stimulus (Ortner et al., 2016). It could therefore be that reappraisal is simply inadequate for such intense and acute moments of fear where the danger is immediate and visceral. While it was previously shown that reappraisal can regulate the threat of acute and painful electric shocks (Yoshimura et al., 2014), the effects were found exclusively for the threat-related anxiety rather than for the negative affect of the painful shock itself. This would limit the translational potential of reappraisal in therapeutic contexts as it may only reduce anxiety but not acute and intense fear. Furthermore, the process model of emotion regulation (Gross, 1998) postulates that reappraisal can only occur after the emotion has been semantically processed (i.e., individuals first have to engage with the emotion before reframing it). Although participants were accustomed to the VR simulation through the ground condition, they did not have training trials with the height condition to familiarize themselves with the rooftop situation. Therefore, there may not have been enough time to process the emotion due to its sudden and direct nature.

Although a simple failure of our intervention could explain the absence of a difference between the reappraisal and the control group, other observations in our study could indicate that there might have been successful emotional regulation in our study. For instance, participants reported a reasonable amount of success in the implementation of the reappraisal strategy with an average score of 73 on a scale from 0 to 100 (see Supplementary Table 7) suggesting that there was likely no issue with applying the cognitive reappraisal strategy by the participants. It should be noted however that lacking measurement within-participants, an isolated rating cannot constitute evidence of successful implementation as ratings may have reflected their capacity for emotion regulation in general. Furthermore, demand characteristics may have influenced the participants' answers as participants may have

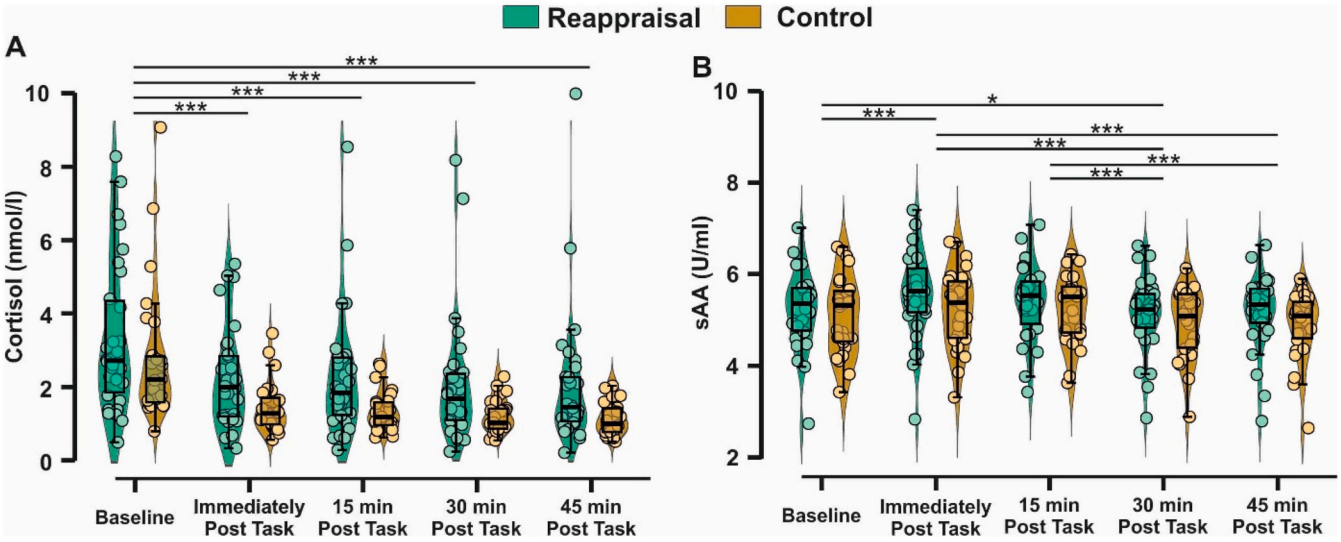


**Fig. 7.** A) Cortisol levels from baseline until 45 min after the VR task had been concluded across the experimental groups (reappraisal, control). B) Same as in A), but for sAA levels. Bars above the boxplots mark significant post hoc effects between the measurements across experimental groups. Boxplots reflect the median, the first and third quartile, and the interquartile range.

been inclined to report success due to their received training. In future studies, it would be useful to expose all participants to the height condition prior to administering instructions to use reappraisal, as a within-participant control. However, a 'passive observation' condition would not control whether participants may be covertly and automatically engaging in re-appraisal (Mauss et al., 2007). In addition to the success ratings, we did not observe the successive increase in right-hemispheric activation in the plank task that was observed in the pre-study by El Basbasse et al. (2023) where no reappraisal intervention took place. This could indicate that individuals in both the experimental and control condition may have successfully downregulated their emotional response. As changes in frontal AIs have been reported using naturalistic emotional stimuli (Berretz et al., 2022b; Packheiser et al., 2021), it is unlikely that the outcome variable was inadequate. It could have been that the reappraisal group showed a regulatory effect resulting in the hypothesized reduced right-hemispheric activation but that the effect was masked by our choice of control. To test the possibility that there might have been emotion regulation in both the reappraisal as well as the control group, we explored if fear ratings and AIs differed across both the reappraisal and control group compared to the pre-study by El Basbasse et al. (2023). This was possible since the methodology was identical compared to the pre-study (except for the added interventions) and the cohort characteristics were comparable (see Methods). We found that participants showed lower fear ratings while on the plank in the present study and showed lower right hemispheric activation (see Supplementary Fig. 1) providing an indication of regulation across both experimental groups. However, it remains unclear why the control intervention may have had a regulatory effect. Being aware and conscious of one's feelings and surroundings has been implicated in the past with reductions in negative affect and the facilitation of emotional regulatory processes (Roemer et al., 2015). Previous studies have shown that mindfulness interventions which specifically focus on awareness of the present moment and current sensations are comparable or even superior to reappraisal strategies in affect regulation (Brockman et al., 2017; Keng et al., 2013), possibly due to them recruiting less cognitive resources (Keng et al., 2013). It could therefore be that our reappraisal intervention was successful but that this effect was masked by our choice of control which comprised elements of mindfulness.

Another observation that contrasted our hypotheses was a lack of cortisol level increase in response to either intervention. A possible explanation why our task did not result in a significant release of cortisol following the intervention stems from the fact that our study did not comprise any psychosocial stress component. In their large-scale meta-analysis, Dickerson and Kemeny (2004) reported that the strongest predictor for elicited cortisol responses were task uncontrollability on the one hand and social-evaluative threat on the other hand. Although our task was not under the participants' control as they had to move alongside the plank as part of the experimental paradigm, the instructions given in both the intervention and control group might have provided participants with a sense of control over the situation regardless. Critically, our study did not encompass any social-evaluative threat component as the participants were projected into the VR environment by themselves. Interestingly, cortisol not only showed no increase but decreased after the task. The decrease in cortisol may have resulted from anticipatory stress in response to a fear-inducing task (Kudielka et al., 2007) as single baseline measures may be insufficient to account for adaptation to the experimental environment (Goodman et al., 2017; Linnig et al., 2025). Another explanation for the decrease in cortisol may relate to the observation that mindfulness interventions can reduce cortisol levels (Sanada et al., 2016). Although meta-analytic evidence for reductions in cortisol following reappraisal interventions is less conclusive (Liu et al., 2019), blunted cortisol responses have been observed in individual studies as well (Crum et al., 2017). It could therefore be that the observed decrease in cortisol levels over time may reflect successful regulation in the experimental and control group.

Although not initially part of our hypotheses and preregistration and thus exploratory in nature, we also measured sAA in addition to cortisol levels as sAA has previously been reported to represent a specific biomarker of fear (Buchanan et al., 2010). The response curve for sAA followed a typical early peak immediately post-task (Het et al., 2020) indicating that our task did recruit the sympathetic nervous system. This observation supports the functional dissociation between sAA and cortisol as markers of acute stress since cortisol seems to be highly specific as a biomarker of psychosocial stress rather than stressful experiences in general (Duncko et al., 2007) whereas sAA secretion is more broadly related to physiological arousal (Schwabe et al., 2008). Since the pre-study conducted by El Basbasse et al. (2023) did not measure cortisol nor sAA, there is unfortunately no reference without intervention to gain further insight if the intervention had any impact on the response of the SAM system or the HPA-axis. Since previous research has reported blunted cortisol and sAA levels following a reappraisal intervention (Jenkins et al., 2018) and reduced cortisol levels are commonly

observed after cognitive behavioral therapy which often uses cognitive reappraisal (e.g., Rosnick et al., 2016), it is possible that the SAM and HPA-axis responses in our study were affected by the interventions. Future research is, however, needed to determine whether and how these biomarkers of stress respond to emotion regulation interventions. Furthermore, since analyses for sAA were conducted in an exploratory fashion, they require independent replication in future studies to confirm the robustness of the findings.

There are limitations for our study that need to be acknowledged. First, we did not include an experimental group without any intervention that could confirm our interpretation that the control group also regulated their emotional state through a potentially mindfulness-like intervention. While we explored these effects by comparing our findings directly to the pre-study of El Basbasse et al. (2023), the conclusions need to be treated with caution as the study, despite its strong similarities, was performed by a different experimenter. Since participants needed to be guided through the experimental protocol, a different experimenter could have affected the results. We, however, consider this explanation less likely due to the intensive training prior to study onset for both experimenters in these respective studies. As our control condition may have engaged regulatory processes through mindfulness, it would have been advantageous to include a condition in which participants are instructed to respond naturally without any specific guidance. However, a potential limitation of this approach is increased variability in strategic choices to regulate as participants may spontaneously engage in different forms of automatic emotion regulation (Mauss et al., 2007) when confronted with highly intense stimuli. A further control condition could involve directing attention toward exteroceptive features of the environment (e.g., colors or spatial characteristics of the VR scene). This approach may limit internally driven regulatory processes by capturing the participants' attention. At the same time, such a condition carries the risk of introducing distraction-based regulation (McRae, 2016) as participants may shift attention away from the fear-relevant aspects of the situation (i.e., the height situation) toward other elements in the simulation (e.g., buildings or textures). Finally, a control condition could be added that explicitly exacerbates the negative effect through for example instructing to ruminate on potential catastrophic outcomes of the situation. Since there were, however, premature terminations of the experimental procedure in our sample, such a condition would require caution and further evaluation from an ethical perspective. Future studies are therefore needed to systematically evaluate which type of control condition provides the most appropriate baseline for studying emotion regulation under conditions of acute threat. Another suggestion for future research relates to the chosen samples as the null result observed in our study could be due to healthy individuals being able to successfully regulate using either reappraisal or a mindfulness-like strategy. It would be interesting to test the effectiveness of reappraisal in VR in clinical samples as the differences between our explicit reappraisal intervention (reappraisal group) and the implicit mindfulness-like intervention (control group) could become more obvious if natural emotional regulation capabilities are impaired. A recent study by Dawel et al. (2024) showed that reappraisal as a coping strategy was most successful for people with additional vulnerabilities like high levels of stress and poor self-efficacy such as patients with borderline personality disorder (BPD). For instance, Dialectical Behavior Therapy (DBT) is currently one of the most empirically supported interventions for BPD (Stoffers-Winterling et al., 2022). Within this framework, patients are taught emotion regulation skills that help them distract themselves and reduce arousal during high-stress situations through reappraisal. In previous studies, four weeks of residential DBT led to significant improvements in overall symptoms in BPD patients; however, aspects of cardiac interoception remained significantly altered (Voelter et al., 2025a,b). The efficacy of VR-based reappraisal may become particularly evident in such clinical populations who display deficits in emotion regulation (Berking et al., 2019; Cui et al., 2024) and could provide a useful tool for testing targeted reappraisal strategies. Another relevant limitation pertains to the fact that our naturalistic scenario lacked several components that create a sense of *realness* as it was mostly visual and did not comprise any other sensory modality beyond the tactile feedback of the plank. Previous research has shown that especially auditory cues increase the sense of presence and make the VR experience more realistic (Honegger et al., 2021). Because the sense of presence in our sample was generally high (see Supplementary Tables 3 and 4), we do not consider this a major issue. An additional limitation pertains to the sample size as it did not reach a priori defined power as outlined in the preregistration suggesting that true effects could have been missed potentially. However, the differences in effects that could have been detected in our experimental design were marginal ($d = 0.6$ vs $d = 0.61$ at 80% power) and our Bayesian analyses mostly revealed moderate to strong evidence for the null hypotheses indicating that our null results are unlikely to have been caused by type-2 errors. Finally, we chose not to include any other emotion regulation strategy, such as suppression or distraction, which are also commonly used strategies (Li et al., 2017). Therefore, we do not know if other strategies might have been successful in downregulating fear responses compared to cognitive reappraisal. Future studies should focus on testing the effectiveness of other strategies using the VR height exposure paradigm.

In conclusion, our study supports previous observations that mere exposure to fearful stimuli is not sufficient to trigger an HPA-axis response but exploratory analyses affirm that sAA may serve as a biomarker of fear. We could not find evidence that subjective fear and physiological correlates of negative affect and stress are reduced after cognitive reappraisal compared to a mindfulness-like control intervention. However, the result pattern indicated that both interventions may have led to successful emotion regulation during the task. Future research is needed to confirm this interpretation by directly comparing reappraisal to different control conditions.

## CRediT authorship contribution statement

**Julian Packheiser:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dirk Scheele:** Writing – review & editing, Resources, Investigation, Funding acquisition. **Victoria Hube:** Writing – review & editing, Methodology, Data curation. **Katja Langer:** Writing – review & editing, Investigation, Conceptualization. **Oliver T. Wolf:** Writing – review & editing, Resources, Investigation, Funding acquisition. **Christopher Maymon:** Writing – review & editing, Software, Methodology, Investigation. **Sebastian Ocklenburg:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Gesa Berretz:** Writing – review & editing, Supervision, Project administration, Investigation, Data curation, Conceptualization.

## Declaration of Generative AI and AI-assisted technologies in the writing process

No artificial intelligence was used in the writing of this manuscript.

## Declaration of competing interest

The authors declare no conflict of interest.

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None.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.yhbeh.2026.105978.

## Data availability

Data and analysis code are available under the following link: https://osf.io/g3p5e.

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