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RESEARCH PAPER

Potential fearful situations in virtual reality — A pilot study assessing the effects of exposure in virtual reality and in vivo on anxious healthy participants in narrow rooms

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Abstract
In vivo exposure is a highly effective but rarely implemented treatment for agoraphobia. Most of the patients receive medication or cognitive therapy without exposure because of a high expenditure of money and time for in vivo exposure. Exposure in virtual reality (VR) is easier to implement but the effectiveness of stimulating fear compared to in vivo exposure is still questionable. Therefore, in this study, the effects of in vivo and VR exposure on subjective symptom burden and heart rate variability (HRV) were assessed. 30 healthy individuals with fears in narrow rooms went through in vivo and VR exposure in a randomized order while HRV parameters (RMSSD, HF) and subjective symptom burden was assessed. Linear mixed models were calculated. The effect of condition (VR vs. in vivo), scenario (varying conditions in narrow rooms) and slot (first 30 s, peak, last 30 s) on RMSSD and HF was assessed. A random effect for participants (random-intercept term) to allow the intercept to vary across participants was

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included. Regarding RMSSD and HF, participants showed significantly higher levels during in vivo exposure compared to exposure in VR (RMSSD: $p = 0.005$; HF: $p < 0.001$), reflecting a stronger activation of the parasympathetic nervous system during in vivo exposure or presumably higher stress levels during VR exposure. This study highlights the necessity of assessing subjective and objective parameters allowing the evaluation of the effectiveness of fear stimulation by exposure approaches.

Introduction

Agoraphobia with or without panic disorder (PD) is characterized by the avoidance of certain places such as busy places, public transport or narrow rooms (Wittchen et al., 2011). Due to the high psychological stress of those affected, they often seek treatment, which makes agoraphobia with or without PD one of the most common diagnoses in outpatient psychotherapy (Wittchen et al., 2011). Cognitive behavioral therapy with exposure to anxiety-inducing situations in vivo (Lang et al., 2009) is considered as ''gold standard" of psychotherapeutic treatment of anxiety disorders, as it shows consistently high therapeutic effects (Deacon & Abramowitz, 2004; Ost et al., 2004). However, studies show that 90% of agoraphobic patients receive psychotropic drugs and only 17% are in psychotherapeutic treatment (Margraf & Poldrack, 2000) with only 8% receiving exposure therapy (Becker et al., 2018; Goodwin et al., 2005). Based on a survey, only 13—17% of psychotherapists conduct exposure therapy (Pittig & Hoyer, 2017). Instead, therapists use interoceptive or in sensu exposure and give exposure in vivo as a homework assignment but rarely accompany patients (Hipol & Deacon, 2013; Klan & Hiller, 2014). Due to persistent avoidance behavior and a limited supply of in vivo exposure therapy, the suffering and the likelihood of chronification of the disorder increase (Colman et al., 2007), which in turn creates additional costs for the health care systems (Wittchen et al., 2011).

As Pittig and Hoyer (2017) described, one reason for the low implementation rate of exposure treatments in vivo could be the high expenditure of time and money, which leads to a rapid exhaustion of the therapy quota. This problem could be solved with exposure therapy in virtual reality (VR). Additionally, when using exposure therapy in virtual reality (VRET), therapists have a higher control of the visited situations, scenarios can be personalized for patients and situations difficult to find or visit can be designed in VR (e. g. flight, crowded places during a pandemic). Accordingly, VRET could compensate for disadvantages of in vivo exposure and shows advantages in application. In agoraphobia, as described above, fear and avoidance in different situations are present and need to be addressed in therapy. In this study, we focused on fear in narrow rooms as one common fear in agoraphobia and which can also be present as a specific phobia (claustrophobia).

A *meta*-analysis by Eichenberg and Wolters (2012) showed, that VRET is effective for the disorders of specific phobia and social anxiety disorder. A reduction in subjectively reported symptoms (e. g. fear, avoidance behavior) and arousal of patients with PD and agoraphobia could be observed after VRET (Botella et al., 2007; Malbos et al., 2013; Pelissolo et al., 2012; Vincelli et al., 2003). In a systematic review by Freitas et al. (2021) regarding the effects of VRET compared with in vivo exposure in anxiety disorders, the authors describe comparable effects of in vivo exposure and VRET in different anxiety disorders. Herein, only two studies with small samples of agoraphobic patients were included (Jang et al., 2000; North et al., 1996). Wechsler et al. (2019) also compared effects of in vivo exposure and VRET for specific phobia (not including studies with claustrophobic participants) and agoraphobia. In vivo exposure and VRET were found to be equally effective for both, specific phobia and agoraphobia regarding subjective symptom burden. In a systematic review, Diemer et al. (2014) found psychophysiological arousal provoked by VRET mainly regarding electrodermal activity. To further understand underlying mechanisms of VR exposure, Diemer et al. (2023) conducted a study assessing effects of different instructions before exposure (focusing vs. distraction) on subjective symptoms and physiological measures. Therein, no effect of the instruction was found on either outcome measure (Diemer et al., 2023). However, the major gap in the empirical evidence is the objective proof of similar physiological measured anxiety and arousal between in vivo and VR exposure, mainly regarding heart rate variability (HRV).

Emotional processing theory (EPT; Foa & Kozak, 1986) proposes that patients' fear networks, consisting of propositions related to stimuli and phobic reactions, need to be completely activated during exposure in order to allow therapeutic change. Therefore, it is proposed that physiological activation can serve as an indicator for a successfully activated network and a probable therapeutic change. Therefore, psychophysiological activation during exposure represents an important predictor of therapeutic change (Foa & Kozak, 1986). These assumptions highlight the importance of assessing psychophysiological parameters during exposure. Nevertheless, some studies showed results in contrast to the assumptions of the EPT. For example, in a *meta*-analysis no association between initial fear activation and treatment outcome was found (Rupp et al., 2017). When a relationship between initial fear activation and therapy outcome was found, the effect was mainly limited to HRV parameters (Craske et al., 2008). Based on these contrary findings, the Inhibitory Learning Theory (Craske et al., 2008, 2014, 2018) was implemented. Herein, in contrast to EPT, habituation and initial activation of the fear network are not considered to be crucial for successful exposure. During exposure therapy, additionally to the

conditioned stimulus a second, non-threat meaning is supposed to be acquired that inhibits the original threat association and this in turn leads to a reduction of fear (Craske et al., 2008, 2018). The development of new inhibitory learning associations are supposed to promote a positive therapy outcome (Craske et al., 2008, 2018). Therefore, possibilities to violate expectancies for the unconditioned stimulus (US) should be heightened in exposure sessions, safety signals should be excluded during exposure (because they are seen as conditioned inhibitors or predictors of the absence of the US) and exposure sessions should be sufficiently massed to violate expectancies of the US and should be conducted in multiple contexts to reduce context-dependence of extinction learning (Craske et al., 2008, 2018).

HRV is an important indicator for measuring stress and anxiety. The feeling of anxiety is characterized by sympathetic activation and vagal/parasympathetic deactivation (Kreibig, 2010). HRV was already assessed in studies investigating effects of in vivo exposure therapy in anxiety disorders (e. g. Alpers & Sell, 2008; Busscher et al., 2013). In past studies, during exposure, more intense HRV responses to symptom provocation at pre-treatment correlate with a greater symptom reduction in various anxiety disorders (Foa & Kozak, 1986). Some studies found a predictive effect of HR on therapy outcome (Michelson et al., 1990) and fear processing (Battaglia et al., 2022; Pappens et al., 2014; Wendt et al., 2018). HRV under resting conditions significantly predicted fear acquisition and extinction (Pappens et al., 2014; Wendt et al., 2018) and an increased parasympathetic activity distinguishing neutral from conditioned stimuli was found during fear learning (Battaglia et al., 2022). This highlights the importance of HRV in fear processing. Though some assumptions of the EPT were not supported in past studies, resulting in the inhibitory learning theory (Craske et al., 2008; Rupp et al., 2017), the assessment of psychophysiological parameters remains relevant to get a holistic picture regarding effects of VR and in vivo exposure.

Past studies showed VR exposure to be effective in treating different anxiety disorders (e. g. Eichenberg & Wolters, 2012) and some studies showed comparable effects of VRET and in vivo exposure (e. g. Freitas et al., 2021). Nevertheless, most studies assessing VRET focus on subjective symptom burden neglecting psychophysiological parameters such as HRV. Therefore, in this study, a sample of healthy participants with fear in narrow rooms as one common fear in agoraphobia was assessed comparing effects of VR and in vivo exposure on subjective symptom burden and HRV to address the current gap in literature regarding the simultaneous assessment of subjective and physiological measures during VR exposure.

Method

Sample

Participants were recruited via announcements at the Johannes Gutenberg-University Mainz, medical practices and online posts. Inclusion criteria were age between 18 and 65 years, ability to speak, read, write in German and giving informed consent. Exclusion criteria were former or current mental disorder, cardiovascular diseases or other diseases influencing the cardiovascular system as well as intake of medication influencing the cardiovascular system. To ensure that participants do not fulfil the criteria for any mental disorder, each interested participant was screened for former or current mental disorders with the SCID-I screening of the DSM-IV (First & Gibbon, 2004; Wittchen et al., 1997). The screening was conducted by trained medical students and supervised by experienced psychologists and psychotherapists. Additionally, interested participants were screened for anxiety in narrow rooms based on the Claustrophobia Questionnaire (CLQ; Radomsky et al., 2001). Participants exceeding the established cut-off for a high risk for claustrophobic events in narrow rooms of M = 0.33 by Napp et al. (2017, 2021) were included in the study. A total of N = 30 participants (86.7% female) were assessed in this study. Age ranged from 19 to 60 years with M = 30.50 (SD = 12.43). 80% of the sample was single and 10% was married and 10% was divorced. 83.3% of the sample had a high school diploma. All of the participants provided written informed consent and the study procedure was conducted in accordance with the Declaration of Helsinki and ethically approved by the Landesärztekammer Rheinland-Pfalz, Germany (2020—15411). Data was collected from November 2021 to December 2022.

Procedure

Participants were invited for one appointment lasting two to three hours wherein both, VR and in vivo exposure was conducted in randomized order. Randomization was performed using a list with random assignment of subject number and order of exposure. First of all, participants were introduced to the nature of fear, explanatory model of anxiety disorders and the idea of exposure. Before starting exposure sessions, participants answered a set of questionnaires (see Clincial assessment) and a three-minute resonance frequency breathing was implemented with a 5 x 5 interval (5 s inhale, 5 s exhale) was conducted for the baseline HRV assessment. An exposure protocol assessing expected reactions and fears was filled out. Then, the first exposure session started either in VR or in vivo depending on randomization. Afterwards, an exposure protocol assessing actual experiences during exposure was filled out before starting with the second exposure followed by answering the questionnaires and exposure protocols a second time.

In VR, six different real-life scenarios of a narrow basement room were presented after each other. Scenarios were recorded using a 360° camera in a 2—3 m^2 basement room without windows and with a ladder leading to a hatch as the exit. The scenarios differed regarding possibility to flight (hatch open/ closed and ladder present or not) and light (bright, dimmed, dark). Scenarios were not randomized in their order of presentation. First, participants were in the bright room with accessible ladder and opened hatch and last, the hatch was closed, the ladder absent and the light was dimmed. The room for in vivo exposure was also 2—3 m^2 in the fifth floor without any window. To parallelize the in vivo exposure with VR exposure, participants went through six different stages where the door of the room

was open/ ajar/ shut/ locked and the light was on/ off. As in VR, in vivo participants started with a lighted room, door opened and ended with a locked door in a dark room. In both conditions, some light came from the closed door (in vivo) or hatch (VR). The light was bright enough for participants to see the outline of the door / hatch / ladder or their own hand in front of their eyes. Reading or distinguishing different colors would not have been possible. Pictures of the room and VR scenarios are provided in Fig. 1. This procedure was supposed to hierarchically increase regarding difficulty and therefore anxiety-inducing potential.

Participants transitioned between scenarios when reporting a decrease in subjective anxiety ratings of at least half of the previously described anxiety (e. g. when anxiety was rated 80% when entering the room, anxiety had to decrease to at least 40% before leaving it). This procedure is common in exposure therapy as a rule of ending exposure sessions (Lang et al., 2012). A table of time spent in each scenario is provided in Appendix A. In both conditions, a break of max. two minutes between scenarios took place while the investigator set up the presentation of the new scenario (VR) or prepared the in vivo room for the next condition (e. g. turning off the light).

Clinical assessment

Before and after each exposure session, the CLQ (Radomsky et al., 2001) was used describing 26 situations where claustrophobic fears can occur. Participants rate these situations from 0 (not at all anxious) to 4 (extremely anxious). Internal consistency for the CLQ is high with Cronbach's α = 0.95 (Radomsky et al., 2001).

When entering and leaving a room, as well as during the exposure sessions, subjective anxiety levels were assessed. Participants were asked for their experienced anxiety at the moment on a scale from 0 (not anxious at all) to 100% (maximum anxiety).

After VR exposure sessions, participants answered the Igroup presence questionnaire (IPQ; Schubert, 2003) and the Simulation Sickness Questionnaire (SSQ; Neukum & Grattenthaler, 2006). The IPQ (Schubert, 2003) measures the sense of presence experienced in a virtual environment. It includes three subscales (spatial presence, involvement, experienced realism) which can be combined into an overall score. The IPQ meets good internal consistency with Cronbach's α = 0.87 (Schubert, 2003). The SSQ (Neukum & Grattenthaler, 2006) assesses sickness symptoms such as

Fig. 1 Pictures of VR scenarios and room used for exposure sessions.

headache, nausea or dizziness elicited by VR. Participants rate the occurrence of 16 different symptoms on a scale from 0 (no perception) to 3 (severe perception). Scores for nausea, oculomotor disturbance, disorientation and total simulator sickness can be computed. Cronbach's α = 0.87 (Bouchard et al., 2007).

Technical devices and heart rate variability

For VR exposure, a standalone Oculus Quest by Meta was used. HRV was obtained with a Polar Watch V800 assessing HRV with a sensor on a chest strap. Intervals for HRV assessment were three minutes and started with entering a new room. Additionally, slots were calculated reflecting the first and last 30 s in one room to assess possible habituation effects as well as one 30 s slot reflecting the peak RMSSD / HF within one room. Peak slots were not calculated for resonance frequency breathing condition. To eliminate extra beats or erroneous values of the R—R interval data, the software Polar ProTrainer 5 (Polar, Germany) was used to post-process the recordings by an automatic filtering process method (filter power: moderate, minimum protection zone: 6 sqm). The root-mean-square successive differences parameter (RMSSD) as well as the heart frequency (HF) were calculated to reflect the activity of the parasympathetic nervous system. Analyses of the parameters were conducted with Kubios HRV Standard (Tarvainen et al., 2014). RMSSD and HF were transformed using logarithm naturalis.

Statistical analyses

A power analysis was conducted with StataBE 17 V5 to calculate an appropriate sample size. The power calculation for repeated measures ANOVA was conducted though mixed models were calculated. As means and standard deviations are equal for each cell, this results in the same sample size for both statistical procedures. Therefore, based on a power of 80%, α = 0.05, 6 repetitions and two conditions (VR vs. in vivo) we assumed matrices including expected effects per time point per condition (δ = 0.68, ρ = 0.50). Based on the literature, VR and in vivo exposure were assumed to show similar effects. Based on this calculation, a sample size of N = 30 was proposed and implemented.

Linear mixed models (LMM) as recommended when analyzing nested data (Hox et al., 2017) were calculated using Jamovi 2.3 (The Jamovi Project, 2020). The effect of condition (VR vs. in vivo), scenario and slot (first 30 s, peak, last 30 s) on RMSSD and HF serving as dependent variables was assessed. Here, RMSSD and HF repeated measurement points were nested in participants as level 2 variables. A random effect for participants (random-intercept term) to allow the intercept to vary across participants was included. Two models were calculated, one for each HRV parameter. Non-significant interactions within the models were excluded stepwise, highest p-values were excluded first.

Results

All of the participants showed values above the established cut-off for a high risk for claustrophobic events in narrow rooms of *M* = 0.33 in the CLQ (Napp et al., 2017, 2021) before exposure sessions ranging from *M* = 0.53 to *M* = 1.24. Table 1 shows subjective levels of anxiety for each scenario during VR and in vivo exposure.

After VR exposure, the mean IPQ score was M = 2.98 (SD = 0.65) ranging from M = 1.69 to M = 4.15. A total of 53.3% did report a general sense of presence in the VR environment of at least M = 3.00. The mean score of spatial presence was M = 2.84 (SD = 0.50), of involvement M = 3.16 (SD = 0.57) and experienced realism M = 2.84 (SD = 1.33). Regarding the SSQ, the most problems occurred regarding oculomotor disturbances (M = 4.96, SD = 3.39) followed by disorientation (M = 3.57, SD = 3.47) and nausea (M = 3.33, SD = 4.15). In total, 6.7% did not report any symptoms of simulation sickness, 73.3% of the participants scored smaller than 10. The maximum score on the SSQ was 27 out of 48.

Mean scores of RMSSD and HF for resonance frequency breathing and exposure rooms can be derived from Tables 2 and 3. Regarding RMSSD, there is a significant main effect of condition (F(1, 1161.00) = 7.96, p = 0.005) with higher RMSSD during in vivo exposure compared to VR exposure.

Table 1 Descriptives subjective anxiety level.

Scenario	Condition	N	Mean	SD	Minimum	Maximum
1	VR	60	13.5	21.0	0.00	100.0
	In Vivo	60	12.2	17.1	0.00	90.0
2	VR	60	21.2	22.3	0.00	90.0
	In Vivo	60	26.4	21.2	0.00	95.0
3	VR	60	21.8	21.3	0.00	90.0
	In Vivo	60	32.7	20.8	0.00	80.0
4	VR	60	26.1	23.0	0.00	80.0
	In Vivo	60	43.6	23.2	0.00	100.0
5	VR	60	17.3	22.4	0.00	90.0
	In Vivo	60	11.4	17.7	0.00	85.0
6	VR	60	27.7	21.5	0.00	90.0
	In Vivo	60	37.9	26.2	0.00	100.0

Note. VR = virtual reality; SD = standard deviation.

Table 2 Descriptives RMSSD.

N	Mean	SD	Minimum	Maximum	
			VR		
RFB	30	39.69	27.74	4.83	145.29
Scenario 1	30	33.72	26.96	3.69	153.88
Scenario 2	30	31.16	20.54	5.24	111.93
Scenario 3	30	33.02	22.45	6.12	127.49
Scenario 4	30	33.45	21.67	8.50	122.43
Scenario 5	30	34.02	26.94	4.98	149.38
Scenario 6	30	34.87	26.25	5.38	146.90
			In Vivo		
RFB	30	39.67	23.24	5.17	111.75
Scenario 1	30	36.61	22.72	6.43	111.55
Scenario 2	30	35.38	22.55	6.50	111.24
Scenario 3	30	36.02	20.06	6.82	90.24
Scenario 4	30	37.92	30.39	4.13	161.76
Scenario 5	30	31.50	16.79	6.06	74.58
Scenario 6	30	33.53	17.92	13.70	85.88

Note. RFB = resonance frequency breathing; RMSSD = Root Mean Square of Successive Differences; VR = virtual reality; SD = standard deviation.

Table 3 Descriptives HF.

N	Mean	SD	Minimum	Maximum	
		VR			
RFB	30	631.17	725.77	8.25	2893.48
Scenario 1	30	458.94	494.83	2.03	1800.27
Scenario 2	30	401.73	387.10	5.00	1733.35
Scenario 3	30	505.20	581.71	5.91	2528.67
Scenario 4	30	490.01	568.76	32.32	2545.21
Scenario 5	30	417.01	457.63	8.64	1739.12
Scenario 6	30	538.08	580.20	5.15	2343.35
		In Vivo			
RFB	30	783.19	870.27	16.88	4334.22
Scenario 1	30	599.46	642.08	7.88	2435.23
Scenario 2	30	594.64	625.97	2.47	2699.80
Scenario 3	30	553.37	588.27	20.26	2191.17
Scenario 4	30	950.13	2478.57	0.44	13802.97
Scenario 5	30	459.76	474.82	10.13	1821.66
Scenario 6	30	536.98	738.45	37.30	3663.99

Note. RFB = resonance frequency breathing; HF = heart frequency; VR = virtual reality; SD = standard deviation.

There is a significant main effect for slot ($F(2, 1161.00) = 18.94$, $p < 0.001$) due to the first 30 s in a scenario significantly differing from peak RMSSD ($t(1161.00) = -5.75$, $p < 0.001$). There is no significant difference between the first and last 30 s in one scenario ($t(1161.00) = -0.97$, $p = 0.333$) and no main effect of scenario was found ($F(6, 1161.00 = 0.42$, $p = 0.863$). Fixed effects parameter estimations for RMSSD can be derived from Table 4.

Regarding HF, there is a significant main effect for condition ($F(1, 1161.00) = 17.73$, $p < 0.001$) and slot ($F(2, 1161.00) = 31.08$, $p < 0.001$) but not for scenario ($F(6, 1161.00) = 1.45$, $p = 0.191$). During in vivo exposure, participants showed significantly higher HF than during VR exposure. The first 30 s in a scenario significantly differed from peak HF ($t(1161.00) = 7.71$, $p < 0.001$) and from the last 30 s in the same scenario ($t(1161.00) = -2.17$, $p = 0.031$). Fixed effects parameter estimations for HF can be derived from Table 5.

Discussion

In this highly standardized and controlled study, the effects of exposure sessions in VR and in vivo were compared regarding subjective symptom burden as well as HRV parameters. The induced fear significantly differed for the different intensities of the stimuli: scenarios showing a fully

Table 4 Fixed Effects Parameter Estimates for RMSSD.

				95% Confidence Interval				
Names	**Effect**	**Estimate**	**SE**	**Lower**	**Upper**	**df**	**t**	**p**
(Intercept)	(Intercept)	3.24	0.10	3.04	3.44	29.03	31.53	<.001
Condition	In Vivo − VR	0.07	0.03	0.02	0.13	1161.00	2.82	0.005
Scenario	2−1	−0.03	0.05	−0.14	0.08	1161.00	−0.54	0.589
	3−1	−0.06	0.05	−0.16	0.05	1161.00	−1.05	0.293
	4−1	−0.01	0.05	−0.12	0.09	1161.00	−0.25	0.806
	5−1	−0.04	0.05	−0.15	0.06	1161.00	−0.78	0.433
	6−1	−0.04	0.05	−0.15	0.07	1161.00	−0.73	0.463
	7−1	−0.07	0.05	−0.18	0.04	1161.00	−1.26	0.209
Slot	2−1	−0.19	0.03	−0.26	−0.13	1161.00	−5.75	<.001
	3−1	−0.03	0.03	−0.09	0.03	1161.00	−0.97	0.333

Note. RMSSD = Root Mean Square of Successive Differences; VR = virtual reality; SE = standard estimation; df = degrees of freedom.

Table 5 Fixed Effects Parameter Estimates for Heart Frequency.

				95% Confidence Interval				
Names	**Effect**	**Estimate**	**SE**	**Lower**	**Upper**	**df**	**t**	**p**
(Intercept)	(Intercept)	5.25	0.23	4.80	5.70	29.03	22.83	<.001
Condition	In Vivo − VR	0.24	0.06	0.13	0.36	1161.00	4.21	<.001
Scenario	2−1	−0.09	0.12	−0.33	0.14	1161.00	−0.77	0.439
	3−1	−0.03	0.12	−0.27	0.21	1161.00	−0.25	0.805
	4−1	0.02	0.12	−0.21	0.26	1161.00	0.20	0.844
	5−1	−0.23	0.12	−0.47	0.00	1161.00	−1.95	0.052
	6−1	−0.16	0.12	−0.39	0.08	1161.00	−1.30	0.195
	7−1	−0.14	0.12	−0.37	0.10	1161.00	−1.13	0.259
Slot	2−1	−0.57	0.07	−0.71	−0.42	1161.00	−7.71	<.001
	3−1	−0.15	0.07	−0.29	−0.01	1161.00	−2.17	0.031

Note. VR = virtual reality; SE = standard estimation; df = degrees of freedom.

lighted room with options to escape (scenario 1, 2, 3) induced less fear than scenarios with dimmed light and no escape options, which induced higher ratings of fear (scenario 4). An almost completely dark room (scenario 6) on the other hand, did induce low levels of fear probably because participants did hardly see the narrow room and possible escape options. Based on this, in future studies, the presentation of a dark room might not be necessary. In general, the scenarios in vivo did lead to higher anxiety ratings than the scenario in VR, except for scenario 1 and 5. During in vivo exposure, anxiety levels in scenario 5 are surprisingly low compared to scenario 4 and 6. Participants could experience less anxiety in scenario 5 because of the opened door as an option to escape compared to scenario 4 with a closed door and no option to escape. Additionally, it seems possible that participants habituate during the different scenarios. Another important aspect, which could also explain differences in VR and in vivo exposure is the possibility of interactions. While participants were theoretically able to interact with the narrow room during in vivo exposure, e. g. by touching the wall or door, this was not possible in VR. Here, they could have moved around in the narrow room but interacting was not possible. As the frequency/quality of interaction was not assessed, this assumption cannot be tested but should be addressed in future studies. Though participants rated in vivo scenarios as more fear-inducing, VR led to more stress reflected by lower levels of RMSSD and HF. This could be due to differences in cognitive processing of VR and in vivo exposure whereby participants expect VR scenarios to be less frightening than real-life situations and therefore give lower ratings. A significant increase of HF was found comparing the first and last 30 s in one scenario for both conditions. This could be a first indication of physiological habituation processes within the exposure sessions.

Regarding HRV parameters (RMSSD, HF), participants showed significantly higher levels during in vivo exposure compared to VR exposure reflecting a higher parasympathetic activation, which could indicate a more relaxed status of the individual during in vivo exposure than during VR exposure as feelings of anxiety are rather characterized by lower parasympathetic activity (Kreibig, 2010). Though participants rated scenarios different regarding fear-inducing potential, this is not shown in HRV parameters

where there were no significant differences between scenarios. Accordingly, subjective and objective measures of anxiety and activation of the autonomous nervous system (ANS) differ. Different past studies also showed a discordance between subjective ratings and psychophysiological measures in healthy participants (Constantinou et al., 2021; Thibodeau et al., 2012) and individuals suffering from social anxiety disorder (SAD; Klumbies et al., 2014). There seem to be different factors influencing the (dis-) concordance of subjective and psychophysiological measures. In SAD, anxiety sensitivity is assumed to play a moderating role (Klumbies et al., 2014). In this healthy sample, no differences in HRV parameters could also reflect successful regulation processes during the experience of fear, which could protect participants from developing a mental disorder due to their fears in narrow rooms. HRV was also shown to be a biomarker for emotion regulation whereby greater HRV was associated with better top-down self-regulation such as emotion regulation (Holzman & Bridgett, 2017).

In general, it was shown that in subjective ratings, in vivo exposure sessions were more fear-inducing than VR scenarios but during in vivo exposure, not only the physiological arousal but also the parasympathetic activation was higher than during VR. As assumed above, participants assuming VR to be less anxiety-inducing could lead to this contradiction. In future studies, it could be helpful to assess participants' attitude towards VR.

Based on the EPT (Foa & Kozak, 1986), an ANS-activation is necessary for habituation and a positive therapy outcome. In this study, parameters reflecting parasympathetic activation were higher during in vivo exposure but reflect a more relaxed and less activated/stressed status of the individuals during exposure. As exposure sessions are supposed to, at least at first, stress individuals to reach a habituation this finding rather supports VR exposure showing a reduced activation of the parasympathetic nervous system. From an inhibitory learning perspective (Craske et al., 2008, 2014), the repetition of exposure in different rooms heightened the possibility to violate expectancies for the US, safety signals were excluded and six different scenarios were presented. Based on the inhibitory learning theory, these aspects could have supported the fear reaction of participants in both VR and in vivo exposure. In this study, aspects promoting exposure-learning based on the inhibitory learning theory were implemented. Based on inhibitory learning, one could assume that scenarios more violating expectations of the participants and presenting less safety signals are also more fear-inducing (Craske et al., 2018). This could explain why scenario 5 is rated as less frightening as an opened door might represent a safety signal, which reduces participants' fear. The study design did not allow to conduct exposure in multiple settings which is crucial for an effective extinction based on assumptions of inhibitory learning (Craske et al., 2008, 2018).

The major strength of this study is the highly standardized and controlled setting. Furthermore, the different degrees in intensity of the stimuli made it possible to observe an intensity progress. Unfortunately, the present study shows some limitations. First of all, the sample size is rather small and there is only a small number of participating men, which could reduce the generalizability of the results. Furthermore, ratings of subjective anxiety during exposure where rather low. It is assumed, that this is mainly because of the healthy sample not showing any diagnosis of anxiety disorder but elevated levels of fear in narrow rooms. Additionally, only one session of exposure with different scenarios was conducted, which does not allow conclusions to be drawn about the effects of comprehensive exposure therapies. Unfortunately, due to technical reasons, it was not possible to conduct both VR and in vivo exposure in the same room, which could influence the participants' reactions.

Based on the findings in this study, VR and in vivo exposure show different effects on subjective anxiety and psychophysiological measures, which emphasizes the necessity of further assess effects of VR exposure and in vivo exposure on subjective as well as psychophysiological measures. In future studies, findings of this study should be addressed by 1) assessing patients with agoraphobia regarding subjective symptom burden and objective HRV parameters during exposure sessions, 2) implementing VR and in vivo sessions over a longer period of time (e. g. exposure therapy) and 3) addressing underlying mechanisms promoting effective exposure based on EPT and inhibitory learning.

In this study, participants showed a higher parasympathetic activation during in vivo exposure than during VR exposure and subjective anxiety ratings were higher for in vivo exposure compared to VR. This finding implies the necessity to further evaluate the effects of VR exposure compared to in vivo exposure and the underlying mechanisms favoring a positive therapy outcome.

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Declarations of interest

None.

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Appendix A. Range and mean value of time in minutes spent by subjects in the individual scenarios

	N	Mean	SD	Minimum	Maximum
			VR		
Scenario 1	30	4.27	1.28	1.33	6.25
Scenario 2	30	4.46	1.09	1.48	6.22
Scenario 3	30	4.08	1.40	1.29	5.45
Scenario 4	30	4.16	1.31	1.59	6.21
Scenario 5	30	3.57	1.56	1.03	5.35
Scenario 6	30	4.33	1.16	1.12	5.46
			In Vivo		
Scenario 1	30	2.75	1.59	1.50	5.00
Scenario 2	30	3.95	1.44	1.28	5.25
Scenario 3	30	4.15	1.25	1.53	5.32
Scenario 4	30	4.87	0.68	2.56	6.32
Scenario 5	30	2.39	1.62	1.46	5.00
Scenario 6	30	4.27	1.20	1.12	5.35

Appendix B. Effect of repetition

To analyze the effect of repeated presentation of the scenarios, we compared subjective anxiety levels when entering a scenario as well as the first 30 s of HF and RMSSD for each scenario separately for both conditions in repeated measures ANOVAs. There was a significant effect in subjective anxiety ratings during VR exposure ($F(5, 145) = 6.93$, $p < 0.001$, $\eta_p^2 = 0.193$). Post hoc analyses with Bonferroni correction revealed significant differences between initial fear in scenario 1 and scenario 2 ($M_{DIFF} = -9.07$, $p < 0.001$), 3 ($M_{DIFF} = -10.07$, $p = 0.027$), 4 ($M_{DIFF} = 13.40$, $p = 0.023$), 6 ($M_{DIFF} = -17.50$, $p < 0.001$) with reduced anxiety ratings in scenario 1. Also, for in vivo exposure a significant effect was found ($F5, 145) = 24.55$, $p < 0.001$, $\eta_p^2 = 0.458$). Herein, in scenario 1 initially less anxiety was reported than in scenario 2 ($M_{DIFF} = -15.33$, $p < 0.001$), 3 ($M_{DIFF} = -22.93$, $p < 0.001$), 4 ($M_{DIFF} = -34.00$, $p < 0.001$) and 6 ($M_{DIFF} = -28.47$, $p < 0.001$) with scenario 1 inducing less anxiety. Additionally, in scenario 2 initially more anxiety was reported than in scenario 5 ($M_{DIFF} = 15.23$, $p = 0.020$) and less than in scenario 4 ($M_{DIFF} = -18.67$, $p < 0.001$). In scenario 3 initially less anxiety was reported than in scenario 4 ($M_{DIFF} = -11.07$, $p = 0.003$) and more than in scenario 5 ($M_{DIFF} = 22.83$, $p < 0.001$). Finally, in scenario 4 initially more anxiety was reported than in scenario 5 ($M_{DIFF} = 33.90$, $p < 0.001$) and in scenario 5 less than in scenario 6 ($M_{DIFF} = -28.37$, $p < 0.001$).

There were no differences for HF during VR ($F(5, 145) = 0.92$, $p = 0.468$) or in vivo exposure ($F(5, 145) = 1.35$, $p = 0.249$). Also, no significant effects were found on RMSSD during VR ($F(5, 145) = 0.45$, $p = 0.810$) or in vivo exposure ($F(5, 145) = 0.27$, $p = 0.930$).

Interestingly, effects in subjective ratings were found but not for HRV parameters. Nevertheless, due to the study design the results cannot be clearly attributed to repetition effects as differences can also be due to the different qualities of the scenarios. This assumption is supported by the results as anxiety ratings do not continuously decline (as can be expected when a habituation happens) but increase in VR and shows variations during in vivo.

The assessed HRV parameters do not seem to habituate to the repeated presentations of different scenarios/conditions in a room. Based on the Emotional Processing Theory one would expect a habituation within one exposure session (Foa & Kozak, 1986). It might be possible that the presentation of different scenarios/conditions in the room were not massed enough to have an effect. Craske et al. (2008, 2014, 2018) assume, that exposure sessions should be sufficiently massed to promote fear extinction. As the scenarios were only presented once, this might be one reason for not finding an effect of repetition on HRV parameters. In future studies, several exposure sessions are necessary. Nevertheless, Craske et al. (2008) also propose, that variability throughout exposure could enhance exposure-based learning in different contexts. Therefore, presenting different scenarios as implemented in this study might be helpful.

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