Virtual reality evoked fear responses and associations with behavioral sensation seeking

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Abstract

Background: Immersive virtual reality (VR) technology presents digital simulations that create the sense of actually experiencing a scenario. VR simulations are persuasive enough to elicit physiological reactions that mirror real-world responses. Prior research suggests that fear responses and sensation seeking are inversely correlated, but that work largely relies on self-reported outcomes and hypothetical scenarios.

Objective: We measure physiological responses to a realistic VR simulation of height exposure and assess behavioral sensation seeking using a laboratory choice task.

Methods: N=57 healthy undergraduates participated in a VR simulation of height exposure and falling (Richie's Plank) that included walking across and stepping off a plank at the top of a skyscraper. Physiological recordings and self-reported state anxiety were collected prior to and during the experience. Behavioral sensation seeking was quantified using an olfactory choice task offering a 'boring' or 'exciting' (risky) option varying in intensity and pleasantness.

Results: The VR experience evoked physiological and self-reported fear. Acrophobia correlated with self-reported fear. Behavioral sensation seeking negatively correlated with both self-reported fear and increased heart rate in males (q<.05). Behavioral and self-reported sensation seeking were uncorrelated. Self-reported fear was uncorrelated with physiological fear responses.

Conclusions: VR simulations can produce lifelike responses to scenarios that are impractical to reproduce in the laboratory. Further, VR facilitates presenting highly abstract or improbable scenarios, expanding the range of topics for behavioral investigations. Given the ever-wider adoption of immersive therapeutics in the clinic, VR research requires further development to evaluate biobehavioral outcomes and interactions with personality factors.

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Original Manuscript

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ABSTRACT

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Conclusion: VR simulations can produce lifelike responses to scenarios that are impractical to reproduce in the laboratory. Further, VR facilitates presenting highly abstract or improbable scenarios, expanding the range of topics for behavioral investigations. Given the ever-wider adoption of immersive therapeutics in the clinic, VR research requires further development to evaluate biobehavioral outcomes and interactions with personality factors.

Keywords: Immersion; simulated; real-life responses; behavioral psychology; risk-taking; phobia; clinical implications; novelty seeking

INTRODUCTION

Immersive virtual reality (VR) produces the functional and behavioral equivalence of actually being in a place—known as "presence" [1-5]. Immersion arises from high-fidelity stereoscopic visual and 3D audio stimuli that respond to user inputs; together, these create an "inclusive, extensive, surrounding and vivid illusion of reality" (pg. 3) [6]. Germane to clinical research, VR can deliver experiences that feel authentic, but would otherwise be too dangerous, costly, or impractical to administer in a laboratory setting [1]. Until recently, research on evoked fear responses generally relied on affective pictures, video, and threat scenarios [7-9]. Extending prior research demonstrating that increasing immersive properties increased evoked responses e.g., [10], VR technology offers the promise of delivering experiences that are interactive, vivid, powerful, customizable, and standardized for studying clinically-relevant outcomes.

Fear is an arousal response to threat stimuli, whereas anxiety occurs while approaching or anticipating a threat [11], although the distinction between fear and anxiety becomes blurred as the threat gets closer or more certain [12]. Unreasonable fear and anxiety elicited by particular stimuli can manifest as specific phobias, which occur in ~10% of the population and are highly comorbid, especially with anxiety, mood, and personality disorders [13]. The fear of heights is the second most common among these specific fears, with a prevalence of 4.5% [13] and is twice as common in females as males [13,14]. The physiological fear response is mediated by the Fight/Flight/Freezing System and autonomic arousal, which can be readily quantified as altered heart rate [11,15]. Longitudinal evidence suggests that evoked physiological responses are more reliable than baseline physiological measures [16]. Further, physiological responses appeared to be more sensitive than self-reported valence to simulated threats when those threats were more lifelike [10]. Prior work indicates that virtual height simulations effectively elicit fear-related arousal responses [5,17]. We surmise that highly realistic fear provocation will be most amenable to investigating associations with objective behavioral outcomes.

Sensation seeking, defined as "the seeking of varied, novel, complex, and intense sensations and experiences, and the willingness to take physical, social, legal, and financial risks for the sake of such experience" (pg. 27) [18] is a putative stress buffer [19]. It is negatively associated with anxiety [17,20,21], risk perception [20,22] and fear responses [23]; although the associations differ by sex particularly on the Experience Seeking dimension; [24]. Unsurprisingly, fear-inducing activities (e.g., hang-gliding, BASE jumping) attract high sensation seekers [25,26]. Moreover, many 'extreme sports' (e.g., bungee jumping, skydiving, ultralight piloting) evoke the fear of falling, a powerful and common 'natural fear' in humans [27].

Sensation seeking is traditionally measured with self-report inventories [28,29]. To quantify sensation seeking and overcome some of self-report's intrinsic limitations, such as social desirability, self-awareness, cultural limitations, and criterion contamination [30-33], we created a behavioral task that models the key aspects of this trait [34]. The Aroma Choice Task (ACT) quantifies sensation seeking behavior as a binary choice between olfactory stimuli varying in intensity, novelty, and riskiness using actual sensory experiences presented in real time. Sensation seeking behavior in this task correlates with self-reported sensation seeking [34], reward-related brain activation [35], and alcohol-induced shifts in reward preference [36]. Given the body of work suggesting that studies relying on low-realism tasks, hypothetical choices, and self-report questionnaires limit neurobehavioral [37] and behavioral genetic [38] conclusions, our objective sensation seeking task quantifies the behavioral trait as described by M. Zuckerman [28].

While virtual height simulations consistently elicit physiological reactions [5,17,39,40], only a few studies have examined relationships between behavior and sensation seeking while in VR [17,41], and no studies, to the best of our knowledge, have tested for associations of physiological fear responses and behavioral sensation seeking. We expect ecologically valid manipulations paired with objective behavioral measures to reveal highly generalizable findings. Here we elicit fear responses with an immersive interactive height exposure simulation [42] and test for associations with sensation seeking behavior. We quantify fear responses as subjective (evoked state anxiety) and objective (evoked physiological arousal). We hypothesize that 1) the virtual height simulation will increase evoked state anxiety and physiological arousal, 2) evoked state anxiety and physiological fear responses will be positively associated, 3) height anxiety will correlate with evoked state anxiety, 4) behavioral sensation seeking and self-reported evoked state anxiety will be negatively associated, and 5) behavioral sensation seeking and physiological fear response will be negatively associated. We also explore potential correlations between behavioral and self-reported sensation seeking.

MATERIALS AND METHODS

Participants

Fifty-seven healthy undergraduate students were recruited from an urban midwestern university and received course credit for participation. Students provided informed consent before study participation, and all procedures were approved by the university's Institutional Review Board. Exclusions included poor sense of smell, extreme sensitivity to odors or volatile chemicals, chronic or current asthma, pregnancy or nursing, or the use of a nasally administered medication (excepting steroids). Physiological data collection was only available partway through the study, so those data were not collected from 21 participants. Technical challenges additionally limited data collection for heart rate and respiration (*n*=1), heart rate only (*n*=2) and respiration only (*n*=1). One participant did not feel well enough to participate in VR so provided only demographic and personality data.

Procedure

Prior to the VR, participants provided demographic information (Table 1) and self-reports of anxiety, height-specific anxiety, and impulsive sensation seeking. All self-report inventories were administered via Qualtrics. They also completed the behavioral sensation seeking task. Physiological recording was initiated before the VR experience and continued until the VR task was completed. Participants were then guided through an immersive fear-inducing VR simulation of height exposure. Self-reported state anxiety was measured again near the end of the fear induction.

Table 1
Participant Characteristics: Demographics and Personality *N*=57

	Female n=40	Male n=17
	Mean (SD) or n (%)	Mean (SD) or n (%)
Age	20.23 (2.94)	20.06 (2.19)
Childhood Income[a]	\$86k (\$35k–\$127k)	\$86k (\$35k–\$141k)
Race: White	21 (53)	12 (71)
Race: Black	6 (15)	2 (12)
Race: Asian	6 (15)	1 (6)
Race: American Indian	1 (3)	0 (0)
Race: Other/Unknown[b]	6 (15)	2 (12)
ZKPQ Impulsive Sensation Seeking	3.82 (2.41)	4.35 (2.57)
ZKPQ Neuroticism-Anxiety	5.50 (3.11)[c]	2.06 (2.08)
ZKPQ Aggression-Hostility	4.24 (1.84)	3.88 (2.20)
ZKPQ Activity	5.05 (2.68)	4.41 (3.24)
ZKPQ Sociability	4.05 (2.52)	3.65 (3.18)
STAI-S	34.26 (9.31)[d]	28.59 (7.87)
Acrophobia Questionnaire-Anxiety	55.60 (18.78)[e]	43.12 (19.69)

ZKPQ = Zuckerman Kuhlman Personality Questionnaire subscales; STAI-S = State Trait Anxiety, Inventory for states; k = thousands of dollars.

[a] Reported as median and interquartile ranges representing the geometric means of the inventory ranges ("<\$10,000", "\$10,000–\$24,000", "\$25,000–\$49,000", "\$50,000–\$74,000", "\$75,000–\$99,000", "\$100,000–\$199,000", "\$200,000–\$500,000", ">\$500,000").

[b] Hispanic ethnicity: n=5 identified as Other/Unknown, n=3 as White, n=1 as American Indian. Hispanic ethnicity did not differ by Sex or Race (Chi-Square, ps>.71)

[c] $t(44.7)=4.83$, $p<.001$

[d] $t(54)=2.19$, $p=.033$

[e] $t(55)=2.26$, $p=.028$

Self-report Inventories

Anxiety. Changes in self-reported anxiety before and during the experience will index evoked fear. The State-Trait Anxiety Inventory for states (STAI-S) is a 20-item questionnaire rated on a Likert-type scale anchored by 'not at all' (1) to 'very much so' (4). Participants report how they currently feel (e.g., *"I feel frightened"*). Total scores range from 20 to 80, with 80 indicating the highest anxiety levels [43]. This questionnaire was used to assess baseline and evoked anxiety, with the subtracted (pre- versus post-VR) difference quantifying evoked anxiety. We changed the administration of the STAI-S during data collection to better capture the emotional state while still in VR. The first 21 participants completed the inventory on a laptop following the experience, but the last 36 participants were queried verbally while still in the headset (standing on the end of the virtual plank), and responses were recorded by the experimenter. Post-VR refers to both ways of measurement. This change was provoked by the concern that STAI-S responses following the experience might be partially influenced by relief (anxiety alleviation) upon termination of the fear-inducing experience. To ensure consistency, both STAI-S inventories were conducted verbally following this change.

Height-Specific Anxiety. The Acrophobia Questionnaire-Anxiety is a 20-item questionnaire that poses hypothetical height-related fear scenarios (e.g., *"looking down a stairway from several flights up"*) and collects responses on a 7-point Likert-type scale anchored by ‘not at all anxious; calm and relaxed’ (0) to ‘extremely anxious’ (6). Total scores ranged from 0 to 120 with higher scores indicating greater levels of height anxiety [44].

Impulsivity and Sensation Seeking. The Zuckerman Kuhlman Personality Questionnaire is a 50-item forced-choice inventory posing self-descriptive statements (e.g., *“I often do things on impulse”*). The five subscales are impulsive sensation seeking, neuroticism-anxiety, aggression-hostility, activity, and sociability. Possible scores on each ranged from one to ten, with ten indicating a high presence of the trait [45].

Behavior

Behavioral Sensation Seeking. The Aroma Choice Task (ACT) is a validated behavioral test of sensation seeking that measures the relative preference for an intense, novel, varied, risky option versus a mild, safe, “boring” option, with odorants delivered in real time. Participants are instructed, *“For the next 12 minutes, you will make choices about some smells. The choice labeled ‘Standard’ will likely be mild and pleasant. The choice labeled ‘Varied’ will likely be stronger and pleasant, but there is a chance that it will be unpleasant. Upon making a choice, please inhale deeply through your nose to receive the aroma.”* Choice ratio, the percentage of ‘Varied’ choices out of a total of 20 binary choice trials (range: 0-100%), yields a single behavioral index reflecting behavioral sensation seeking (designed after self-reported sensation-seeking trait descriptions) [28,29]. The original ACT was developed with an air dilution olfactometer [34], but a simpler, manual version yielded analogous results [36]. We further modified the task to deliver 20 trials instead of the original 40, as our prior work indicated that the first 20 trials accurately captures the trait with lower participant burden [34].

Physiological recording

Heart rate, respiration, and skin conductance was collected using the BioRadio™ (Great Lakes Neurotechnologies; Cleveland, OH) and skin electrodes plus a respiratory inductance plethysmography belt, with data logged on a laptop computer. Baseline measurements were collected prior to VR (“pre-VR”) and recording continued until the VR experience was completed. The baseline measures quantified stable heart rate and respiration, collected during breathing exercises (instructions were for normal breaths, long deep breaths, short fast breaths, and breath holding; each for 20 seconds). Skin conductance data were not analyzed.

Virtual Reality

The fear of falling from heights is an ‘innate’ fear, i.e., non-reliant on associative conditioning [27] or locomotion experience [46], and nearly universal [47], that is highly generalizable and reliable for eliciting potent fear responses. The immersive height exposure simulation was the “Richie’s Plank Experience” [42] delivered with a Meta Quest 2 head-mounted VR display. Widely used in VR research on fear responses and behavior [41,48], the paradigm presents a realistic city view from heights (~80 stories) while participants walk onto and off the end of a narrow plank protruding from the skyscraper. The height illusion was conveyed by audio and visual simulation of extreme exposure to open space, which included wind noise and birds flying below the participant. Immersion was maximized with haptic feedback from a real wooden plank (“2×8” [2m×19cm×4cm]) spatially registered to the virtual plank. The wooden plank was slightly warped, thus creaked and shifted with human weight. Although verbal instructions were provided as needed, researchers refrained from unnecessary verbal or physical interaction during the experience to preserve presence. Figure 1 illustrates participants’ view at the heights in the paradigm.

Analytical Strategy

Physiological data collected by BioCapture™ (Great Lakes Neurotechnologies; Cleveland, OH) software were modeled in VivoSense v3.4. All statistical tests were performed in SPSS v29.0.2.0 (IBM; Armonk, NY). Analyses were stratified by sex as prior work demonstrated important interactions by sex between anxiety and sensation seeking [24] and by sex and elements of sensation seeking [28,49]. VR-induced increases in anxiety and physiological arousal were tested with paired *t*-tests between baseline and the moment of stepping off the virtual plank. Change scores were calculated for self-reported state anxiety and physiological measures (post-VR minus pre-VR scores). These were correlated with behavioral sensation seeking, each other, and height-specific anxiety. The potential effect of changing the STAI-S assessment method (computer versus verbal inside VR) was tested with independent-samples *t*-test. Appropriate protection against familywise error in hypothesis tests was provided by limiting the overall false discovery rate (q) to 5%; here, by setting alpha = .0278 [50]. Tests evaluating baseline sex differences (Chi-Square for categorical, *t*-test for continuous) reported in Table 1 were uncorrected and descriptive in nature. All in-text data are reported as mean ±SD.

RESULTS

Demographics and Personality

Females reported higher baseline levels of anxiety than males (Neuroticism-Anxiety, State anxiety, and height-related anxiety, ps<.034). No other sex differences were detected (Table 1).

Evoked Fear (Increased Anxiety)

The VR experience increased anxiety in both males $t(16)=5.29$, $p<.001$, 28.59 ±7.87 and 44.76 ±17.27, $q<.05$ (pre- and post-VR respectively) and females $t(38)=9.50$, $p<.001$, $q<.05$, 34.26 ±9.31 and 54.05 ±14.51 (Figure 2A). The increase in anxiety was not significantly different before versus after the data collection method change, $p=.75$ (see *Self-report Inventories/Anxiety*).

Physiological Arousal

The VR experience increased heart rate in both sexes, $t(8)=3.84$, $p=.005$, $t(23)=6.99$, $p<.001$, $q<.05$, males and females respectively. Similarly, the VR experience increased respiration in both sexes, $t(8) = 3.06$, $p=.016$, and $t(24)=5.35$, $p<.001$, $q<.05$ (Figure 2B,C).

Evoked Fear and Physiological Response

Fear (evoked state anxiety) did not correlate with changes in heart rate (ps=.60 and .79 for males and females respectively) nor respiration (ps=.47 and .48). Baseline anxiety also was uncorrelated with changes in heart rate (ps=.70 and .29) and changes in respiration (ps=.71 and .17).

Acrophobia and Evoked Fear

Fear of heights (acrophobia) was correlated with evoked state anxiety in males $r(15)=.606$, $p=.010$ and females $r(38)=.410$, $p=.009$, $q<.05$ (Figure 3).

Behavioral Sensation Seeking and Evoked Fear

High intensity preference (ACT scores) negatively correlated with evoked state anxiety (delta STAI-S) in males $r(15)=-.559$, $p=.020$, $q<.05$, but not females ($p=.67$) (Figure 4). Preference for high intensity was not correlated with baseline STAI-S scores in females ($p=.61$), although there was a trend in males, $r(15)= -.465$, $p=.060$.

Behavioral Sensation Seeking and Physiological Fear Response

High intensity preference (ACT scores) negatively correlated with increased heart rate in males $r(7)=-.771$, $p=.015$, $q<.05$, but not females ($p=.54$) (Figure 5). Increased respiration was uncorrelated in both sexes (*p*s>.28).

Behavioral and Self-reported Sensation Seeking

High intensity preference did not correlate with self-reported sensation seeking in males ($p=.47$) or females ($p=.72$); collapsing across sex did not permit detection of an association ($p=.89$).

DISCUSSION

We found support for our hypotheses concerning VR's capacity to evoke fear (self-reported changes in state anxiety and physiological arousal) and the association between evoked fear and fear of heights. We found support for the negative association between evoked fear and behavioral sensation seeking in males, but not females. Interestingly, evoked fear measures were uncorrelated. Behavioral and self-reported sensation seeking were uncorrelated. These findings suggest that VR experiences possess sufficient ecological validity to elicit subjective and objective fear responses mirroring responses to real-world scenarios, moreover, responses to the digital experience reflect established associations with other traits (acrophobia and sensation seeking).

VR continues to offer considerable promise for clinical and research applications alike. The expanding reach of VR is facilitated by better immersion technology, decreasing cost, creative applications, and wider adoption. While VR has long been used to administer exposure therapy [51,52] and treat pain [53,54], emergent applications target increasingly abstract constructs [55,56]. Germane to the current study, VR applications effectively treat various anxiety disorders (e.g., specific phobias, social anxiety disorder, panic disorder) in randomized controlled trials, producing effects comparable to conventional treatment and significantly better than passive controls [57]. In addition to promising efficacy data, providers and patients appear eager to adopt VR methods, as suggested by two recent reports on integrating VR in clinical practice [58,59]. VR technology also promises to increase translatability of basic neuroscience, with virtual paradigms for humans closely matching well-established animal paradigms. The elevated plus-maze—the gold standard in rodent anxiety research—can be instantiated for human participants [17] to connect basic neuroscience in rodents with human behavioral data. Other behavioral paradigms widely used in rodents, such as conditioned place preference, can be accurately reproduced in humans using VR [60]. Thus, the role and relevance of VR for both laboratory research and clinical practice is expected to grow substantially in the near future. Our use of VR permits testing extant theoretical knowledge in more lifelike settings and experiences, and when paired with behavioral tests, yields increasingly objective outcomes.

VR can add knowledge to mature bodies of research, like approach-avoidance, by presenting realistic simulations in humans. Approach-avoidance describes behavior that orients organisms toward positive and away from negative stimuli, respectively [61]. Approach-avoidance tendencies are likely rooted in evolutionary factors, primarily through sexually divergent selection pressure [62]; that is, reproductive fitness optimized by exploratory behaviors in males [63,64] and harm avoidance in females [65,66] in hunter-gatherer societies. The extremes of the approach-avoidance continuum are marked by exaggerated attention on reward or threat cues [67]. These tendencies emerge from overactive brain reward/motivational systems [68] and underregulated brain threat systems [69] for approach, and conversely, overactive brain threat systems [70] and underactive brain reward systems [71] for avoidance. Sensation seeking and fear represent aspects of approach and avoidance, i.e., opposing processes that modulate threat responses, such that high sensation seekers are less physiologically responsive to threat stimuli than low sensation seekers. One study testing fear responses in high and low sensation seekers found that high sensation seekers showed no response to threatening stimuli (versus control stimuli), whereas low sensation seekers produced an 8-fold increase in electromyographic response to threats [23]; interestingly, self-reported emotional reactivity did not differ by group—supporting the value of objective measurements. Males are higher sensation seekers than females (particularly thrill/adventure seeking and disinhibition) [72,73], but the relationship between sensation seeking and fear appears to differ by sex. Investigating this relationship as an interaction with sex, Blankstein [24] found that Sensation Seeking Scale (SSS) [21] total score negatively correlated with anxiety reactivity (Activity Preference Questionnaire) total and subscales (Social and Physical) at *r*s>.43, *p*s<.01 in males, but not in females (*r*s<.07). However, a similar study found a number of negative correlations between the SSS and anxiety-related items (S-R Inventory) in both sexes [74], indicating mixed results in detecting sex interactions with approach-avoidance correlations. The lack of consilience in prior work might be explained by either *(i)* dependence on self-report inventories, with self-reported fear and sensation seeking often incongruent with objective measures [36,75], and/or *(ii)* high anxiety and low sensation seeking in females producing restricted ranges (ceiling and floor effects) making correlations difficult to detect. Future well-powered studies, ideally using precise behavioral tasks, should bring clarity to these possible associations.

We did not detect correlations between self-reported fear and physiological responses to height exposure. While this is perhaps a surprising result, prior work suggests that self-reported fear does not necessarily reflect biological responses. In a real-world test, participants' self-reported fear of crime did not differ between walking down a dimly-lit path (versus well-lit control), but the dimly-lit path participants' heart rate increased 17% (*p*=.002), with controls remaining unchanged [75]. Even patients with anxiety disorders do not accurately report the degree of physiological responses to stress in laboratory tests [76,77]. This lack of concordance may be explained by individual differences in interoceptive ability [78]. The disconnection between self-reported traits and objective measures extends to behavioral assessments of impulsivity [79], empathy [80], and risk preference [81]—suggesting that the incongruence extends well beyond fear and anxiety. A recent report on associations between interoceptive ability and autobiographical memory [82] indicates that interoceptive perception (physical self-awareness) relates to episodic recall (cognitive self-awareness), and suggests the intriguing possibility that individual differences in these domains may be governed by some larger self-awareness meta factor.

Some limitations should be acknowledged. First, the sample would benefit from more power. The homogeneity of the sample—reflecting typical undergraduates—is predominately female and white, precluding well-powered direct comparisons by sex and potentially limiting generalizability. While we reported effects in males that did not appear in females, more confidence in sex effects would emerge from a better-balanced sample. Finally, the truncated sample of subjects providing physiological data was suboptimal.

The current report demonstrates the potential of VR for neuroscience and clinical research. The immersive nature of this nascent technology permits entirely new avenues of investigation and permits research on humans that would be dangerous or impractical to study with real stimuli. We believe that the potential of VR to unite human and animal paradigms heralds a new translational era wherein strictly controlled animal neuroscience experiments can be accurately reproduced in humans. Beyond research and education, VR is now well-established as a clinically valuable tool in a wide range of psychiatric disorders [83], with especially compelling benefits offered by VR exposure therapy [84] and pain alleviation [85]. We expect ever-wider adoption of VR applications in the clinic and continued expansion in the laboratory research domain.

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ABBREVIATIONS
ACT: Aroma Choice Task
SSS: Sensation Seeking Scale
STAI-S: State Trait Anxiety Inventory-State
VR: Virtual Reality

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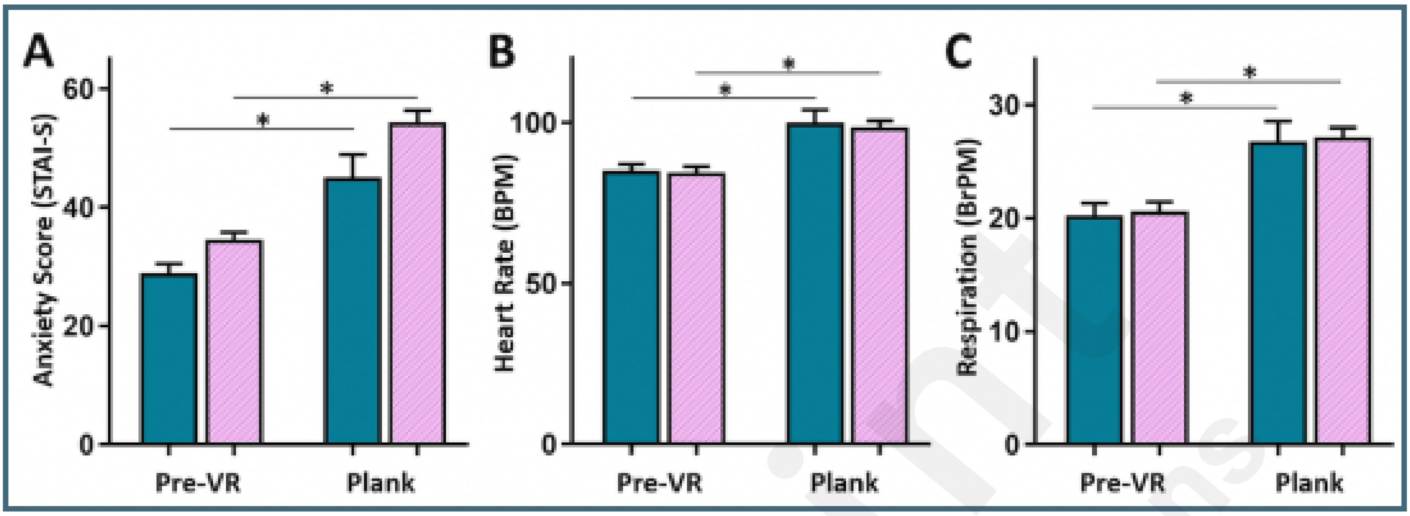
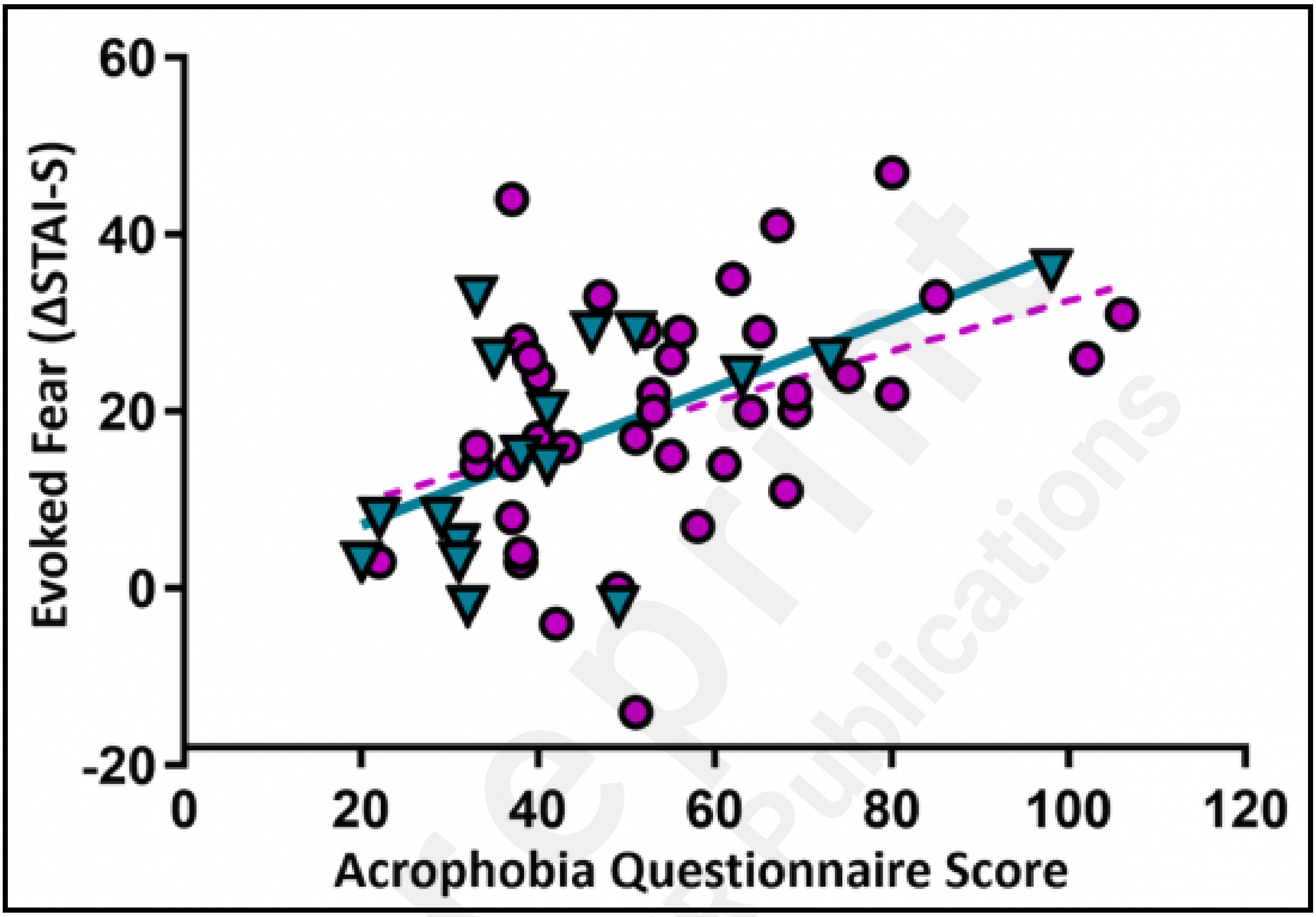
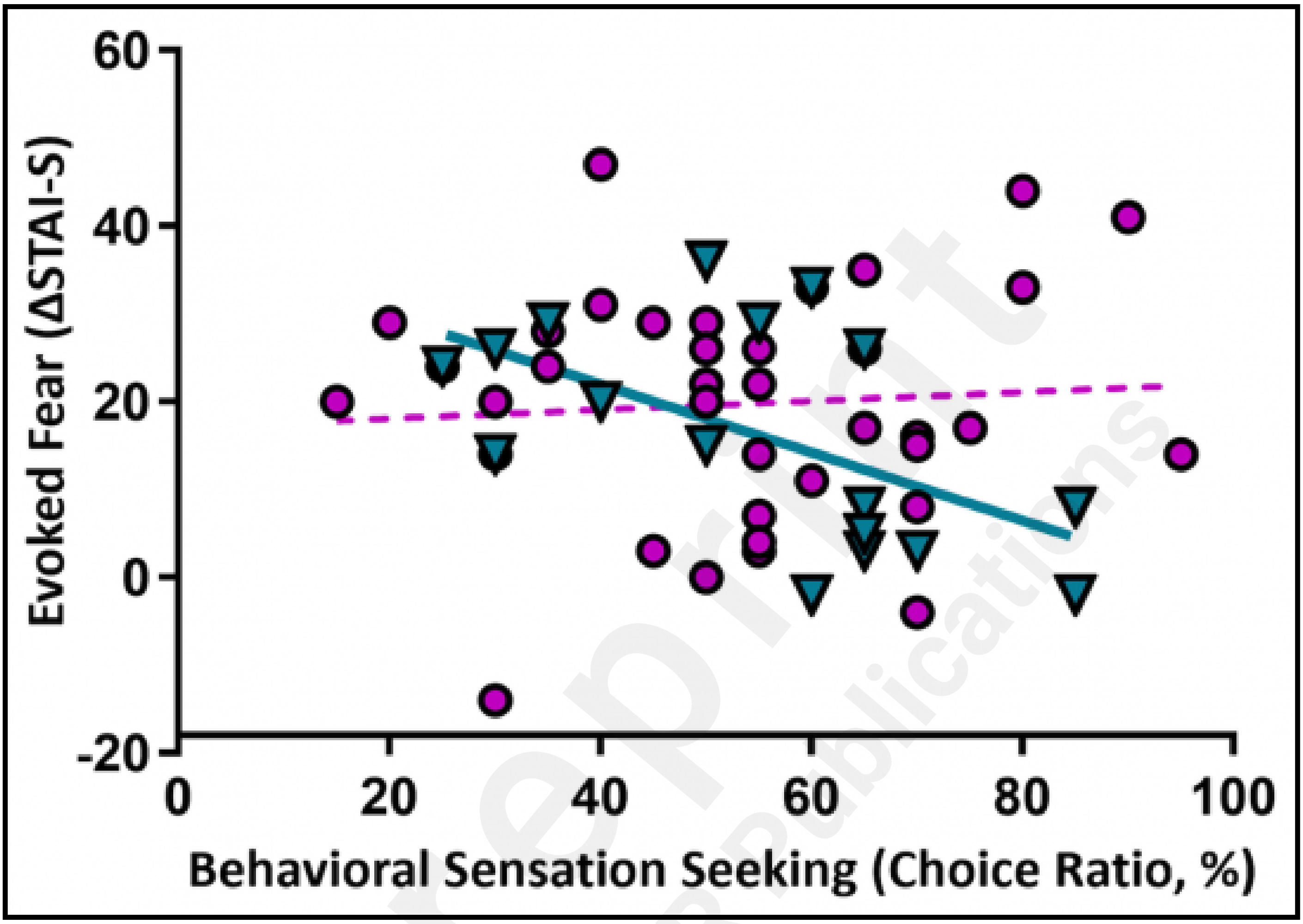
Supplementary Files

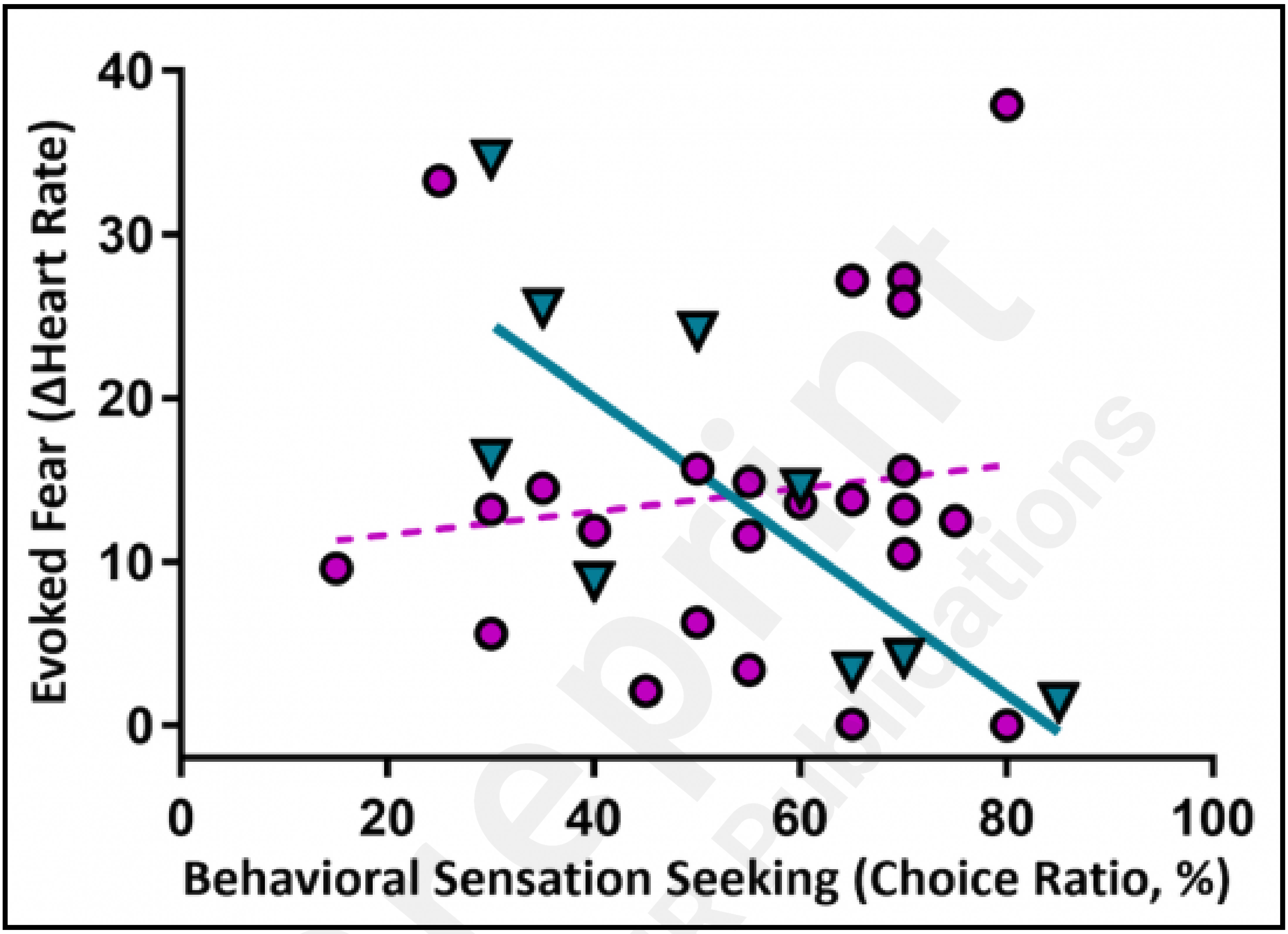
Figures

Participants' View. The headset presents an illusion of extreme height exposure in a city environment. The view shown is taken from midway on the plank (plank shown in foreground).


A
Anxiety Score (STAI-S)
60
40
20
0
*
*
Pre-VR
Plank
B
Heart Rate (BPM)
100
50
0
*
*
Pre-VR
Plank
C
Respiration (BrPM)
30
20
10
0
*
*
Pre-VR
Plank


Evoked Fear (ΔSTAI-S)
60
40
20
0
-20
0
20
40
60
80
100
120
Acrophobia Questionnaire Score


Evoked Fear (ΔSTAI-S)
60
40
20
0
-20
0
20
40
60
80
100
Behavioral Sensation Seeking (Choice Ratio, %)


40
30
20
10
0
Evoked Fear (ΔHeart Rate)
0
20
40
60
80
100
Behavioral Sensation Seeking (Choice Ratio, %)