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Social stress in an interaction with artificial agents in virtual reality: Effects of ostracism and underlying psychopathology

Marius Rubo [a,b,*], Simone Munsch [b]

[a] Cognitive Psychology, Perception and Research Methods, Department of Psychology, University of Bern, Fabrikstr. 8, CH-3012 Bern, Switzerland
[b] Clinical Psychology and Psychotherapy, Department of Psychology, University of Fribourg, 2, Rue de Faucigny, CH-1700 Fribourg, Switzerland

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ABSTRACT

Social stress can emerge from situational as well as dispositional factors. Here we tested in direct juxtaposition how ostracism in a Cyberball game and underlying psychopathology levels both influence subjective and objective stress markers in an interaction with artificial agents in virtual reality (VR) in 80 participants from a student population. Ostracism led to moderately enhanced subjective stress and negative mood but not to alterations on objective markers of stress. By contrast, underlying psychopathology levels were associated with substantially stronger alterations on subjective stress markers and were additionally associated with reduced eye gaze at virtual agents' heads, larger pupil size, larger high-frequency pupil-size variability, higher heart rate and reduced high-frequency heart-rate variability. Effects for social anxiety, general anxiety and depression levels were overall similar with largest effects on objective stress markers linked to general anxiety. These findings contest the suitability of the Cyberball game as a model for real-life ostracism but demonstrate the utility of gaze and physiological data in predicting psychopathology levels during interactions in VR. These findings furthermore highlight the need for data security solutions when using social VR applications where rich data streams are exposed publicly.

1. Introduction

Social interactions are a key part of everyday life and are pervasively sought after by humans (Baumeister & Leary, 2017), but both situational and dispositional factors can turn a social encounter into a stressful experience. Even brief episodes of ostracism (merely being ignored without being explicitly informed that one is being excluded) can cause stress and negative affective reactions in healthy individuals (Williams, 2007). Conversely, individuals high on social anxiety (Morrison & Heimberg, 2013) and other forms of psychopathology (Redcay & Schilbach, 2019; Schilbach, 2016) can experience stress even in neutral or inclusive social situations.

A common experimental induction of ostracism is the Cyberball paradigm (Williams & Jarvis, 2006) where participants are excluded in a ball-tossing game with (computer-controlled) artificial agents. This paradigm was shown to induce distress and negative emotional responses (Hartgerink, van Beest, Wicherts, & Williams, 2015). Findings on physiological stress markers were more mixed and include increased heart rate (HR) (Iffland, Sansen, Catani, & Neuner, 2014a; Kothgassner et al., 2021) or no effects on heart rate (Iffland, Sansen, Catani, & Neuner, 2014b; Kothgassner et al., 2021; Williamson, Thomas, Eisenberger, & Stanton, 2018), increased high-frequency heart rate variability (HF-HRV) (Liddell & Courtney, 2018), blunted electrodermal activity (Iffland et al., 2014b) or no effect on electrodermal activity (Iffland et al., 2014a), increased (Zwolinski, 2011), decreased (Bass, Stednitz, Simonson, Shen, & Gahtan, 2014) or unaffected cortisol levels (Kothgassner et al., 2021). While a majority of studies misleadingly informed participants that artificial agents were being controlled by other humans, a small number of studies observed stress reactions in a Cyberball game even when participants were correctly informed about the artificiality of their co-players (Jauch, Rudert, & Greifeneder, 2022; Kothgassner et al., 2014; Zadro, Williams, & Richardson, 2004). The game can be played on a computer monitor but also in virtual reality (VR) (Kothgassner et al., 2021) which allows for more lifelike social behavior and was observed to elicit enhanced reactions to social cues (Rubo & Gamer, 2020).

Individuals suffering from social anxiety experience social stress in situations which may be experienced as pleasant by others due to a persistent fear of other people's scrutiny (Morrison & Heimberg, 2013). While some individuals are so debilitated by their social

* Corresponding author at: Cognitive Psychology, Perception and Research Methods, Department of Psychology, University of Bern, Fabrikstr. 8, CH-3012 Bern, Switzerland.
E-mail address: marius.rubo@unibe.ch (M. Rubo).

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anxiety that they may receive a diagnosis of a social anxiety disorder (SAD), a considerable proportion of individuals experience "subclinical", but nonetheless stressing fears in or in the anticipation of social situations (Stein, Walker, & Ford, 1994). In addition to fear, socially anxious individuals can experience symptoms of depersonalization/derealization (DPDR) which are characterized by an experience of unreality in one's sense of self and the outside world (Hoyer, Braeuer, Crawcour, Klumbies, & Kirschbaum, 2013). As a behavioral marker of social stress, social anxiety (at moderate levels) was linked to a relative avoidance of looking into others' faces (Daly, 1978; Hessels, Holleman, Cornelissen, Hooge, & Kemner, 2017; Langer, Lim, Fernandez, & Rodebaugh, 2017; Rubo, Huestegge, & Gamer, 2020; Schneier, Rodebaugh, Blanco, Lewin, & Liebowitz, 2011; Terburg et al., 2016) — a phenomenon which could be replicated in VR (Dechant, Trimpl, Wolff, Mühlberger, & Shiban, 2017) — although not all studies observed this phenomenon (Rösler, Göhring, Strunz, & Gamer, 2021; Weeks, Heimberg, & Heuer, 2011). Social anxiety was additionally associated with higher heart rate during a social interaction (Rösler et al., 2021) and reduced HF-HRV at rest (Alvares et al., 2013; Pittig, Arch, Lam, & Craske, 2013). Note, however, that such observations are not specific to social anxiety, but alterations in social functioning and stress in social situations are observed across a range of mental disorders (Redcay & Schilbach, 2019; Schilbach, 2016) and reduced attention towards faces may be a more general hallmark of psychopathology (Rubo, Käthner, & Munsch, 2023). Likewise, reduced HF-HRV was similarly observed in other anxiety disorders (Chalmers, Heathers, Abbott, Kemp, & Quintana, 2016; Pittig et al., 2013) as well as a correlate of depression symptoms (Alvares, Quintana, Hickie, & Guastella, 2016; Neyer et al., 2021). More generally, mounting evidence points to a considerable overlap in symptoms and physiological correlates in people suffering from mental problems, with a single factor, general psychopathology (abbreviated as *p*), explaining a substantial proportion of the variance across disorders (Kotov et al., 2021). The observation that different aspects of psychopathology are linked through a common factor has led some authors (e.g., (Caspi et al., 2013)) to suggest that empirical relationships between behavioral or physiological markers with a specific facet of psychopathology should be assumed to more generally represent a relationship with p unless specificity is established empirically, i.e., a similar relationship with other facets of psychopathology is tested and not observed.

In addition, it may be argued that the specificity of findings should not only be tested within the field of psychopathology, but also across broader descriptions of inter-individual variation. A widely used model for characterizing trait differences between individuals is the Big-5 personality model (Heine & Buchtel, 2009) which shows partial overlap with conceptualizations of psychopathology: not only do factors correlate with each other (Asendorpf & van Aken, 1999; Kaplan, Levinson, Rodebaugh, Menatti, & Weeks, 2015) but neuroticism was also found to correlate positively with social anxiety (Kaplan et al., 2015) and extraversion was found to correlate negatively with depression levels (Watson, Stanton, Khoo, Ellickson-Larew, & Stasik-O'Brien, 2019). It is important to note that, although diagnoses for mental disorders are defined as dichotomous categories, measures of psychopathology are typically distributed continuously in the population, which was taken to suggest that descriptions of psychopathology should more strongly highlight the phenomenon's dimensional character (Haslam, Holland, & Kuppens, 2011) and integrate with broader conceptualizations of personality (Bagby & Widiger, 2018). Similarly to variables describing psychopathology, personality factors were linked to alterations in social attention, with Wu, Bischof, Anderson, Jakobsen, and Kingstone (2014) reporting a positive correlation between extraversion as well as agreeableness and face preferences, Guy, Azulay, Kardosh, Weiss, Hassin, Israel, and Pertzov (2019) reporting a negative correlation between conscientiousness and face preferences and Rubo et al. (2023) reporting a positive correlation between extraversion, agreeableness as well as openness with face preferences.

Situational and dispositional factors may both add to, but also interact in eliciting social stress in individuals. In a qualitative synthesis of research in the field, Reinhard et al. (2019) report on signs of an overall enhanced vulnerability to social stress in psychopathology, but also on mixed findings with regards to the specificity and stability of reactions to ostracism. For instance, Hoyer et al. (2013) observed heightened levels of DPDR during a stressing situation in individuals suffering from SAD compared with healthy controls, while Iffland et al. (2014b) did not find social exclusion to disproportionately affect individuals with SAD. Gutz, Renneberg, Roepke, and Niedeggen (2015) observed a stronger increase in threat to fundamental needs between inclusion and exclusion in SAD, while patients with borderline personality disorder showed overall increased threat to fundamental needs. Jobst et al. (2015) found a disproportionately strong effect on negative mood following social exclusion in patients suffering from chronic depression. Kumar, Waiter, Dubois, Milders, Reid, and Steele (2017) found larger amygdala, insula, and ventrolateral prefrontal cortex activation but similar subjective stress ratings in patients with major depressive disorder compared with healthy controls.

The present study assessed subjective and objective markers of social stress resulting from ostracism in a Cyberball game and from underlying psychopathology levels (see Fig. 1 for an overview). While these may be seen as two separate research questions — with ostracism inducing social stress across individuals and psychopathology levels of individuals being associated with heightened levels of social stress across situations — both are included here to allow for a direct comparison of their effects. An inclusion of differing predictors of social stress within the same data set additionally allows to investigate their interactive effects. In characterizing participant's psychopathology levels, we focused on the assessment of social anxiety levels which are particularly closely linked to the experience of social stress in social situations (Morrison & Heimberg, 2013), but additionally assessed generally anxiety, depression levels and personality which often cannot be delimited clearly from each other empirically (Caspi & Moffitt, 2018; Rubo et al., 2023). Signs of social stress were assessed using a comparatively encompassing set of both subjective and objective markers. On the subjective level, we assessed stress levels, mood and symptoms of depersonalization/derealization (DPDR) (Hoyer et al., 2013). On an objective level, we assessed avoidance of gaze at agents' faces (Rubo & Gamer, 2020; Shaffer & Ginsberg, 2017; Vatheuer, Vehlen, Dawans, & Domes, 2021), pupil dilation and pupil size variability (an index for the sympathetic nervous system) (Hepsomali, Hadwin, Liversedge, & Garner, 2017; Kret & Sjak-Shie, 2018; Peysakhovich, Causse, Scannella, & Dehais, 2015), heart rate (HR) (Vrijkotte, van Doornen, & de Geus, 2000), and high-frequency heart-rate variability (HF-HRV, an index for parasympathetic activation) (Kim, Cheon, Bai, Lee & Koo, 2018). We hypothesized that ostracism, but also underlying psychopathology levels would be associated with increased social stress both on subjective and objective measures and that ostracism would disproportionately affect individuals high on psychopathology.

2. Methods

2.1. Subjects, materials and procedure

80 participants (62 women, 16 men, 2 persons who did not wish to disclose or did not identify with one of the two genders; mean age = 23.49 years, *SD* = 4.88, Range = [18, 44], recruited at a university, 46 from Switzerland, 27 from Germany, 3 from another European country, 4 from another non-European country) took part in this study. As compensation for their participation, participants could receive course credits or take part in a tombola where they could win a shopping voucher. This study's sample size and obtained measures were preregistered (AsPredicted 55857, https://aspredicted.org/yk3ji.pdf). Data that support the findings of this study are available at https://osf.io/8hz9s/. The study conformed to the principles expressed in the

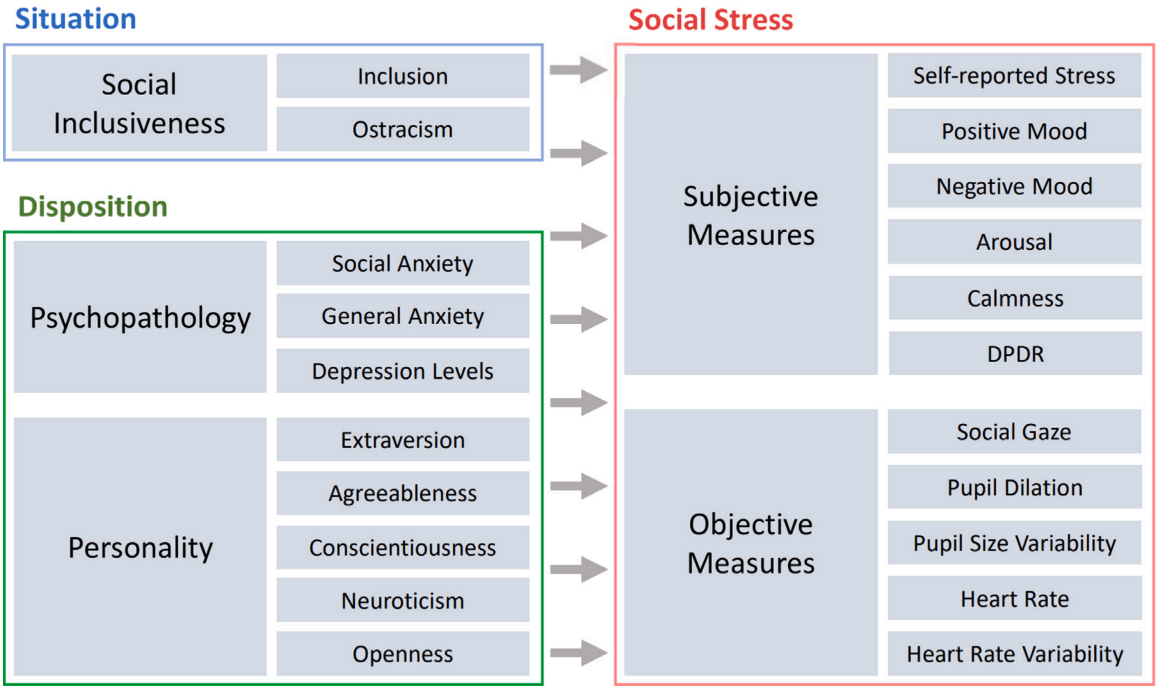

Fig. 1. Study Overview. We compared the influence of a situational variable (social inclusiveness) and participants' dispositional factors (psychopathology and personality) on several subjective and objective markers which were linked to social stress. DPDR: Depersonalization/Derealization.

Declaration of Helsinki and was approved by the local ethics committee at the University of Fribourg (Ref-No. 2022-812). With alpha set to 5%, a sample size of 80 is sufficient to detect an effect of d = .32 in a two-sided comparison in a paired t-Test with a power of 80% or to detect an effect of r = .31 in a two-sided correlation with a power of 80%. Participants were eligible to participating if they reported no neurological disorder, did not take centrally acting medication and had normal vision or corrected-to normal vision with contact lenses. After completing an informed consent form, a demographic questionnaire and trait questionnaires, participants received more detailed information about the VR situation and their task in it. Unlike several studies in the field, participants were not given the erroneous information that artificial agents were being controlled by real humans in another room. Before entering the VR, participants were instructed to place electrodes for electrocardiogram (ECG) measurements on their upper bodies and the experimenter started an ECG data recording. Participants then wore a VR headset and VR controllers and engaged in two rounds of a VR Cyberball game where they were either included or excluded from receiving the ball. Conditions (inclusion vs. exclusion) were delivered in a randomized order. After each round, participants filled out questionnaires assessing state variables.

2.2. Virtual reality apparatus and software

The VR setup consisted of an HTC VIVE® Pro Eye VR system (https://www.vive.com) with a built-in eye-tracker (www.tobii.com) and Valve Index Controllers (https://www.valvesoftware.com/) for hand and finger tracking. Software was developed using Unity 3D (https://unity.com). Participants took ownership over a virtual avatar which they could select from a total of 18 pre-configured virtual characters. Body movements were mapped onto the avatar based on participants' head, hand and finger movements using inverse kinematics (http://root-motion.com/). Gaze direction and blinking were mapped onto the avatars' eyes using live data from the eye-tracker. In order to enhance the sense of being located in the situation as oneself (as opposed to playing an anonymous character), the experimenter took a photo of the participant which was being displayed on a poster in the virtual situation behind the participants.

At the beginning of each round, participants found themselves located in a virtual town environment where a female narrating voice explained the situation and the game. Participants could see their avatar in a virtual mirror which allowed them to look into their own eyes an experience that their gaze behavior was visible in the virtual world. Participants then practiced catching and throwing in VR by throwing a ball towards a target for roughly four minutes. Ball catching was facilitated for participants by equipping the hand of their choosing with a baseball glove which automatically caught balls which touched it. Grabbing and throwing the ball with the other hand was controlled using the controller's grab detection.

Next, the artificial agents appeared in the scene and a triangular ball game started (see Fig. 2). In both conditions, the first ten throws by the agents were directed to the other agent or the participant with an equal probability. In the inclusion condition, this behavior continued for another 30 throws while in the exclusion condition, the remaining 30 throws were carried out only among the two artificial agents, excluding the participant from receiving the ball. If the ball could not be caught by the participant or one of the two artificial agents, it was again shot at the specific player automatically in order to allow for the game to continue. Both conditions ended with the three players standing closer together around a small fireplace for two minutes. Here, the narrating voice informed participants that they had no task but could merely wait for a short time. Objective data (gaze, pupil, ECG) from this phase were taken to represent the reflective phase in the experience of social inclusion or exclusion. Finally, the narrating voice informed participants that they could take off the VR headset and contact the experimenter. During the game, the experimenter was present in the same room and located behind a curtain.

Control of the artificial agents' movements was designed with the goal to display a naturalistic and variegated behavior in order to facilitate an ascription of mind and experience to agents (Kim et al., 2018; Pan & Hamilton, 2018). We used a form of *Motion Matching* (Holden, Kanoun, Perepichka, & Popa, 2020) where in specific time points (e.g., when the participant or an agent throws a ball), a database of movement animations is searched for the animation which best fits the situation and is subsequently played on the artificial agent. Our database of animations consisted of several hundred movements

Fig. 2. Virtual environment in which the Cyberball game took place. Standing together in a triangle, the participant can be excluded from participating in a ball game when the two artificial agents throw the ball towards each other (left) or be included by receiving the ball from a player (right). Artificial agents show a naturalistic catching and throwing behavior. A video showing the agents' behavior in action is available under https://osf.io/6tcns.

(e.g., catching a ball coming from the left-hand player in a specific location and throwing it to the right-hand player; not being able to catch a ball but reaching in its direction; turning from one side to another as other players are throwing the ball to each other etc.). Transitions between animation recordings were carried out using interpolation in order to create a continuous movement. A more detailed description of this procedure will be subject to a separate publication.

2.3. Self-report trait measures

Personality Traits were assessed using the BFI-10, a brief version of the Big Five Inventory (Rammstedt & John, 2007) which includes extraversion, agreeableness, conscientiousness, neuroticism, and openness to experience. Items ask for the agreement with statements on perceptions about oneself and are scored from 1 (strongly disagree) to 5 (strongly agree).

Social Anxiety levels were assessed using the Social Interaction Anxiety Scale (Mattick & Clarke, 1998). Items are rated on a 5-point Likert scale (0 = Not at all characteristic or true of me, 4 = Extremely characteristic or true of me).

Anxiety and Depression levels were assessed using the Patient Health Questionnaire-4 (PHQ-4, Kroenke, Spitzer, Williams, & Löwe, 2009). Participants are asked to rate depression and anxiety symptoms for the past week on a 4-point Likert scale ranging from 0 (not at all) to 3 (nearly every day).

Summaries of questionnaire data are shown in Table 1. Five (6.25%) participants had scores on social anxiety which were above the proposed cutoff (of ≥ 34) to discriminate between patients and controls (Brown et al., 1997). Proposed cut-offs for anxiety and depression subscales of the PHQ-4 (scores of ≥ 3)(Löwe et al., 2010) were reached in 13 (16.25%) participants with regards to anxiety and 5 (6.25%) participants with regards to depression levels. For further analysis, scores on each scale were compared to the whole distribution and values beyond 3 standard deviations from the mean were replaced with values at 3 standard deviations from the mean. This was the case for one score on SIAS (3.56 SD above the mean), one score on general anxiety (3.09 SD above the mean) and one score on depression levels (4.55 SD above the mean). Each scale was then z-standardized. In order to assess the overlap between individual facets of psychopathology in the present sample, principal component analysis (PCA) was performed with no rotation applied (see Fig. 3). Three factors exhibited eigenvalues of larger than 1 (2.77, 1.20 and 1.17), with the strongest factor exhibiting an eigenvalue more than twice the size of the second strongest factor. The strongest factor was positively and similarly correlated with social anxiety (r = 0.80, 95% CI [0.70, 0.87], t(78) = 11.72, $p < .001$), general anxiety (r = 0.76, 95% CI [0.65, 0.84], t(78) = 10.35, $p < .001$) and neuroticism (r = 0.74, 95% CI [0.62, 0.82], t(78) = 9.61, $p < .001$), but also showed very large correlations (according to (Funder & Ozer, 2019)) with depression levels (r = 0.57, 95% CI [0.40, 0.70], t(78) = 6.17, $p < .001$) and extraversion (r = −0.67, 95% CI [-0.78, −0.53], t(78) = −7.96, $p < .001$). We take the first component in this analysis to represent general psychopathology levels in participants and use it as the most parsimonious and conservative description of inter-individual variability in the present sample. In an additional and explorative analysis, we linked dependent variables to each of the assessed facets of psychopathology (social anxiety, anxiety and depression levels).

Table 1
Trait questionnaires.

	M	SD	Range	Possible range	α
BFI-10 Extraversion	3.69	0.98	[1, 5]	[1, 5]	0.76
BFI-10 Agreeableness	3.72	0.74	[2, 5]	[1, 5]	0.31
BFI-10 Conscientiousness	3.69	0.73	[2, 5]	[1, 5]	0.42
BFI-10 Neuroticism	3.01	1.05	[1, 5]	[1, 5]	0.73
BFI-10 Openness	3.81	0.96	[1, 5]	[1, 5]	0.57
SIAS (Social Anxiety)	19.06	10.1	[0, 55]	[0, 80]	0.86
PHQ-4 Anxiety	1.48	1.15	[0, 5]	[0, 6]	0.59
PHQ-4 Depression	1.18	1.06	[0, 6]	[0, 6]	0.56

Range: Actual range of scores in the present sample. Possible range: Minimum and maximum scores that can be reached on each measure. α: Cronbach's alpha.

2.4. Subjective measures of social stress

Subjective stress was assessed using a single question ("How stressed are you at the moment?") which was rated on a slider from 0 to 100 (Shiban et al., 2016).

Mood Positive mood, negative mood, arousal and calmness were assessed using scales suggested by Wilhelm and Schoebi (2007) on sliders from 0 to 100.

Depersonalization/Derealization (DPDR) symptoms were assessed using the German translation (Michal et al., 2004) of the state version of the Depersonalization/Derealization scale (CDS-State) (Sierra & Berrios, 2000). Current experiences of depersonalization and derealization are rated using a slider from 0 to 100.

We additionally assessed Presence (IPQ) (Schubert, Friedmann, & Regenbrecht, 2001), Simulator Sickness (VRSQ) (Kim, Park, Choi & Choe, 2018) and agents' ascribed capabilities for agency and experience (Malle, 2019). Observations on these measures are reported in the Supplementary Methods, Results and Discussion.

2.5. Objective measures of social stress

2.5.1. Gaze at heads and pupil size measures

Before each round, the eye-tracker was calibrated using a 5-point calibration. Eye-tracking data (gaze direction from both eyes and pupil size) were recorded at a target sampling rate of 60 Hz (frequency of Unity's Update loop). Since framerates in real-time computer simulations can show variation, data were resampled to 100 Hz using linear interpolation for further analysis. Eye-tracking data from two participants were removed from the dataset due to technical problems in data collection resulting in more than 50% loss of data. Gaze direction and pupil size were removed from the data set during eye blinks as well as

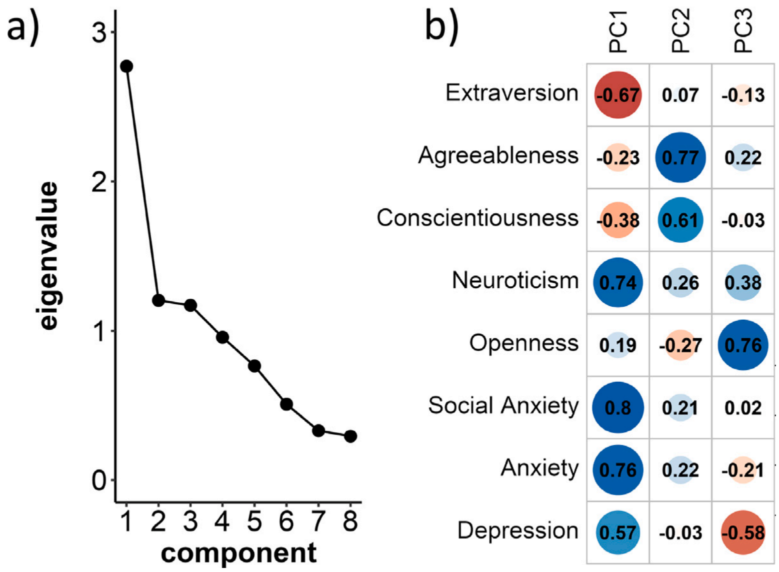

Fig. 3. Results of a principal component analysis (PCA). (a) shows the factors' eigenvalues in a scree plot, while (b) shows correlations between the first three factors (which had an eigenvalue > 1) and each variable. The large first factor was taken to represent general psychopathology.

100 ms before and after each blink. Removed pupil size measures were replaced using cubic interpolation.

For each region of interest (ROI: the artificial agent's heads) individually, gaze direction from both eyes (represented as 3D rays) was transposed to represent deviations in the horizontal and vertical direction following a procedure described in Rubo and Gamer (2020). For each time point, we then computed the lowest deviation from either agent's head by either participant's eye's gaze direction or the averaged gaze direction from both eyes (*ROI deviation*). This procedure allows to detect gaze at a ROI even when a participant suffers from strabismus (Stidwill, 1997) where only the gaze direction form one eye (but not from the other eye or from a combined gaze ray) represents the participant's overt attention or when participants show an over-adjustment of vergence in VR (Lamb, Brundin, Luque, & Billing, 2022), where no individual eye but only a combined gaze ray represents the participant's overt attention. In the present study, results did not differ qualitatively if this procedure was replaced with an assessment only based on a combined gaze ray or the two individual eyes. Eye gaze samples were then categorized to rest on an agent's head if it missed a head's center by less than 2 degrees — a range which was found to capture more than 90% of gaze samples when participants do not wear glasses (Schuetz & Fiehler, 2022). We additionally computed a complementary measure for participants' gaze towards agents' heads which avoids a dichotomous categorization of gaze. Here, we first log(x+1)-transformed ROI deviation values in order to emphasize differentiation of small values (e.g., to attribute a larger difference in social gaze to ROI deviation values of 1 and 21 degrees compared to 101 and 121 degrees). Resulting values were then interpolated to lay on a scale from 0 (representing gaze in the opposite direction of a ROI) and 100 (representing gaze directly at a ROI) and were named *Social Gaze Index*. For each participant and condition, we then computed the percentage of time that gaze lay on an agent's head as well as the average of the Social Gaze Index.

Pupil size data for each participant were low-pass filtered using a second order Butterworth filter with a cut-off frequency of 5.9 Hz (Peysakhovich et al., 2015). In addition to pupil size, Peysakhovich et al. (2015) suggested to assess frequency spectra as a related measure which is less strongly influenced by luminance (a factor which cannot easily be held constant in more naturalistic situations as in the present study). We performed a spectral analysis of pupil size for low (0–1.6 Hz) and high frequency (1.6–4 Hz) bands by windowing timeseries using a Hann window, FFT-transforming and cutting to only include positive frequencies. We used Welch's periodogram with segments of 30 s length and an overlap of 50%. To obtain power spectrum density (PSD), resulting power spectra were scaled by multiplying the squared spectrum magnitude with two and dividing by the product of the sampling frequency and the sum of the squared samples of the window function. Power values were converted to dB for each frequency spectrum with a reference of 0.0001 s^2/Hz. Peysakhovich et al. (2015) suggested to take a ratio of LF and HF power (which are both positively associated with mental load) as index for mental load. Here we additionally report on both power spectra individually. We again computed average values for each participant and condition.

2.5.2. *Heart rate and heart rate variability*

Electrocardiograms (ECG) were recorded using Bitalino devices (https://www.pluxbiosignals.com/) at a sampling rate of 1000 Hz. Due to technical problems, ECG data from 9 participants were unavailable. QRS complexes were first detected automatically using an algorithm described by Elgendi, Jonkman, and De Boer (2010). Data were then visually inspected individually and corrected manually if needed. Equidistantly sampled RR interval series were constructed using cubic spline interpolation. The first 30 s of ECG data in the reflective phase were removed from the analysis due to possible effects from the previous phase which differed in physical activity levels between the conditions. Heart rate (HR, in beats per second) was defined as 60 divided by then mean of the RR interval series (in seconds). In order to obtain frequency power spectra, RR interval series were first downsampled to 4 Hz using bandlimited interpolation. We then used the same approach to compute power spectra as for the computation of power spectra in pupil size described above. High-frequency heart rate variability (HF-HRV) was then defined as signal power between 0.15 Hz and 0.4 Hz.

2.6. *Data processing and statistical analysis*

For all dependent variables, observations were compared to the distribution of observations separately within each condition (inclusion vs. exclusion) and values beyond 3 standard deviations from the mean were replaced with values at 3 standard deviations from the mean. This was the case for six observations on stress (with values located 3.13 and 3.27 SD above the mean in the inclusion condition and values 3.09, 3.30 and 3.30 SD above the mean in the exclusion condition), one observation on negative mood (a value 3.37 SD above the mean in the exclusion condition), four observations on depersonalization/derealization (a value 3.19 SD above the mean in the inclusion condition and values at 3.01, 3.04 and 4.40 SD above the mean in the exclusion condition), three observations on gaze on conspecifics' heads (with values 3.33 and 4.09 SD above the mean in the inclusion condition and a value 3.78 SD above the mean in the exclusion condition), one observation on social gaze index (a value 3.08 SD above the mean in the exclusion condition), one observation on pupil LF (a value 3.12 SD below the mean in the inclusion condition), one observation on pupil HF (a value 3.60 SD below the mean in the inclusion condition) and one observation on HF-HRV (a value 3.44 SD below the mean in the inclusion condition). In order to control for changes occurring throughout the course of the experiment, all dependent variables where centered within each round. From the first to the second round, there was a significant decrease in arousal (d = 0.26), depersonalization/derealization (d = 0.17), pupil size (d = 0.24) and heart rate (d = 0.10).

Data were analyzed using R for statistical computing (R. Core Team, 2013). Compared to the pre-registered analyses, we included three additional dependent variables (social gaze index as well as power in the two individual power bands in pupil size variability) and provide a broader, more data-driven analysis, but additionally control for multiple testing. As a most direct comparisons between the two conditions we first used one Sample t-tests. Cohen's *d* was calculated as the mean difference between both measurement scores divided by the pooled standard deviation. Correlations of psychopathology levels with dependent variables were assessed using Pearson correlations. In order to compare Cohen's *d* values and Pearson r values, *d* values were divided by the square root of the sum of the square of *d* and 4 (Ruscio, 2008). Corrections for multiple comparisons were carried out individually for each predictor (ostracism, psychopathology) and each group of dependent variables (all subjective measures, all objective measures) using a procedure described in Benjamini and Hochberg (1995). To assess interactions between the condition and other predictors, we additionally computed linear mixed models with random intercepts for each participant id. Analyses were repeated for each individual facet of psychopathology (social anxiety, general anxiety, depression levels) to exploratively assess the convergence of findings between these facets. Reported main effects are estimated in models with no interaction terms. In all analyses, alpha was set to .05.

3. Results

3.1. Effects of ostracism on social stress

Descriptive statistics (before centering within rounds) and a comparison between inclusion and exclusion condition are shown in Table 2. In both conditions, participants reported overall high levels of positive mood and calmness (> 70 on scales from 0 to 100) and low levels of stress, negative mood and depersonalization/derealization (< 30). Ostracism led to more stress (d = 0.42) and negative mood (d = 0.28) but was not associated with changes on other subjective or objective measures.

3.2. Effects of psychopathology on social stress

Fig. 4 shows correlations between the condition (with Cohen's d effect sizes transferred to r) as well as psychopathology with the assessed subjective and objective dependent variables. Statistics are reported in detail in Supplementary Results. After adjusting for multiple comparisons, psychopathology was significantly correlated with stress (r = .37), positive mood (r = −.43), negative mood (r = .44), calmness (r = −.53), depersonalization/derealization (r = .38), gaze on heads (r = −.20), social gaze index (r = −.22), pupil dilation (r = .23), pupil HF (r = .17), Heart Rate (r = .27) and HF-HRV (r = −.20). All significant effects were substantially larger compared with effects of ostracism. In a direct comparison, effects of underlying psychopathology on markers of social stress were substantially larger compared with effects of ostracism both with regards to subjective (t(5) = 4.32, p = .008; d = 1.77) and objective variables (t(7) = 7.86, p < .001, d = 3.67).

In an additional explorative analysis, we computed correlations between dependent variables and individual facets of psychopathology (see Fig. 5). With regards to subjective measures, all statistically significant correlations between general psychopathology and dependent variables were replicated with each individual facet of psychopathology. With regards to objective measures, correlations between individual facets of psychopathology and dependent variables generally showed a similar pattern compared with correlations between general psychopathology dependent variables, with high correlations between correlation coefficients for general psychopathology and social anxiety (r = .96 [95%-CI = .77, .99], t(6) = 7.98, p < .001), general anxiety (r = .98 [95%-CI = .89, .99], t(6) = 11.79, p < .001) as well as depression levels (r = .96 [95%-CI = .79, .99], t(6) = 8.40, p < .001). Nonetheless, statistically significant correlations between general psychopathology and dependent variables were only directly replicated in general anxiety levels, namely gaze on heads (r = −.20), gaze index (r = −.22), pupil dilation (r = .27), pupil HF (r = .24), Heart Rate (r = .28) and HF-HRV (r = −.20).

3.3. Interactions between ostracism and psychopathology

Results of linear mixed models predicting subjective and objective markers of social stress from general psychopathology as well as the three individual facets of psychopathology assessed in the present study are shown in Supplementary Results. We found no evidence for interactions between ostracism and psychopathology levels.

4. Discussion

The present study assessed subjective and objective markers of social stress in response to ostracism from artificial agents in VR and as a function of underlying psychopathology in participants. Ostracism was associated with increased subjective stress and increased negative mood, but not with any objective markers of stress. Underlying psychopathology levels were associated with higher levels of stress, negative mood and DPDR as well as with lower levels of positive mood. In direct comparison, effects of underlying psychopathology levels on subjective measures of stress were substantially larger compared with the effect of ostracism, although psychopathology levels were overall moderate and on the level commonly observed in the general population (Byrow, Broeren, Lissa, & Peters, 2016; Hinz et al., 2016; Rubo et al., 2023). Additionally, while ostracism was not associated with any objective markers of stress, psychopathology levels were associated with reduced gaze at artificial agents' heads, larger pupil dilation, enhanced high-frequency pupil size variation, higher heart rate and reduced high-frequency heart-rate variability. An additional explorative analysis suggests that these findings may be more strongly linked to anxiety and less strongly linked to social anxiety and depression levels, although patterns were overall similar. We found no evidence for enhanced susceptibility to ostracism in psychopathology.

The largest effect of ostracism observed in the present study were enhanced levels of subjective stress (d = 0.42), whereas a meta-analysis by Hartgerink et al. (2015) notes a substantially larger total ostracism effect of d > 1.4. Several factors may have contributed to the comparatively smaller effects in the present study. Firstly, Hartgerink et al. (2015) observed funnel plot asymmetry, a sign of possible publication bias and possibly inflated effect sizes. Perhaps most importantly, while main outcomes in the present analysis were stress, mood and DPDR symptoms, Hartgerink et al. (2015) observed the largest effects in those 58% of studies which investigated a threat to fundamental needs (*need-threat* scale) as primary outcome. On all other subjective measures, ostracism elicited effects of only d ≈ 0.70 (for immediate reactions on

Table 2
Subjective and objective markers of stress following social inclusion and ostracism.

	Possible range	Social inclusion			Ostracism			Cor	Comparison				
		M	SD	Range	*M*	SD	Range		t	df	*p*	*p*.adj	*d*
Stress	[0 100]	11.96	14.44	[0.00 56.06]	20.62	23.36	[0.00 92.88]	0.51	3.81	79	<.001	.001	0.42
Positive Mood	[0 100]	75.39	18.50	[25.50 100.00]	72.42	21.22	[17.50 100.00]	0.68	1.59	79	.116	.174	0.15
Negative Mood	[0 100]	18.83	16.97	[0.00 70.59]	24.27	20.56	[0.00 75,00]	0.77	3.78	79	<.001	.001	0.28
Arousal	[0 100]	42.61	19.36	[00.00 100.00]	43.47	18.83	[1.33 90.67]	0.73	0.38	79	.701	.701	0.03
Calmness	[0 100]	74.91	17.84	[24.33 100.00]	72.70	18.79	[25.00 100.00]	0.83	1.81	79	.074	.148	0.12
DPDR	[0 100]	8.65	10.36	[0.00 39.98]	9.65	11.31	[0.00 46.34]	0.83	1.29	79	.199	.239	0.09
Gaze on Heads	[0 100]	11.23	7.15	[0.18 33.98]	12.16	9.37	[0.23 41.07]	0.63	1.13	77	.261	.536	0.11
Social Gaze Index	[0 100]	44.03	8.43	[30.27 68.39]	45.01	9.83	[23.34 71.58]	0.72	1.15	77	.255	.536	0.11
Pupil Size		4.42	0.71	[2.82 6.04]	4.43	0.66	[2.86 6.24]	0.95	0.26	77	.797	.797	0.01
Pupil LF		44.75	2.14	[38.06 49.62]	44.76	2.21	[39.78 51.07]	0.62	0.01	77	.989	.989	0.00
Pupil HF		26.81	2.15	[22.57 32.28]	26.74	2.01	[22.63 31.76]	0.72	0.53	77	.595	.911	0.04
Pupil LF/HF		1.68	0.11	[1.42 1.99]	1.68	0.11	[1.40 1.93]	0.43	0.40	77	.691	.911	0.04
Heart Rate		91.60	11.88	[71.07 122.40]	91.13	12.13	[70.40 121.57]	0.95	1.12	70	.268	.536	0.04
HF-HRV		19.53	4.53	[5.63 29.60]	19.64	4.45	[7.27 30.82]	0.69	0.33	70	.742	.797	0.02

Comparison of subjective and objective measures between the inclusion and exclusion conditions. Possible range: Minimum and maximum scores that can be reached on each measure (if applicable). Range: Actual range of scores in the present sample. Cor: Pearson correlation coefficient of measures in both conditions as index of measurement reliability. p.adj: p values adjusted for multiple comparisons. DPDR: Depersonalization/Derealization, Gaze on Heads: percentage of time gazed at agents' heads. Social Gaze Index: Value from 0 to 100 indicating gaze towards as opposed to away from agents' heads. Pupil LF: power in low-frequency component (0 Hz to 1.6 Hz) of pupil size fluctuation, Pupil HF: power in high-frequency component (1.6 Hz to 4 Hz), Pupil LF/HF: ratio between LF and HF power, HF-HRV: power in high-frequency component (0.15 Hz to 0.4 Hz) in heart rate fluctuation.

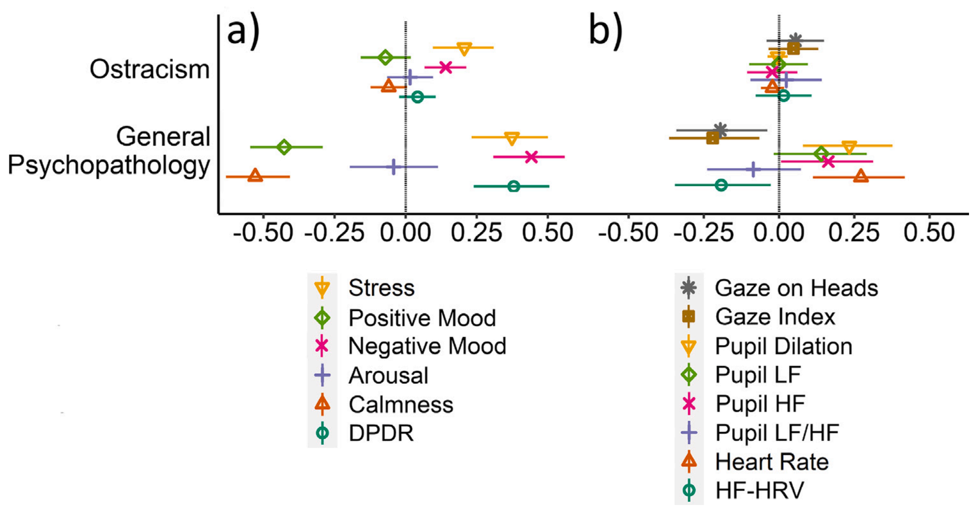

Fig. 4. Correlations between ostracism and general psychopathology with (a) subjective and (b) objective measures. Lines represent 95%-CIs. DPDR: depersonalization/derealization symptoms, Pupil LF: low-frequency component of pupil size oscillations, Pupil HF: high-frequency component of pupil size oscillations, HF-HRV: high-frequency heart rate variability.

intrapersonal and interpersonal variables; data assessed at later time points were associated with smaller effects). Threats to fundamental needs are commonly assessed using a 12-item scale (Zadro et al., 2004) which distinguishes a need to belong, a need for self-esteem, control and meaningful existence. Problematically, a more thorough investigation into the validity of the scale did not confirm such distinct needs but rather a general sense of threat following the Cyberball game (Gerber, Chang, & Reimel, 2017). Additionally, some items lack a direct conceptual link to *fundamental* human needs per se but may more broadly capture discontent with the testing situation (e.g., "I felt somewhat frustrated during the Cyberball game", "I felt I had control over the course of the game"). Not only were previous ostracism effects comparatively moderate with regards to measures of stress outside of the need-threat scale, but similarly as in the present study, participants in previous studies reported markedly more positive compared to negative emotions even following ostracism (Kothgassner et al., 2021; e.g., Kothgassner et al., 2017). This observation appears to contrast the profound negative impact of real-world ostracism (Bernstein, 2016; Riva, Montali, Wirth, Curioni, & Williams, 2016; Zadro, 2000). Additional evidence for the notion that ostracism effects in Cyberball studies may not be as strong as previously estimated comes from studies on neural activation patterns during the game. While initial studies observed enhanced activity in the dorsal anterior cingulate cortex (dACC; an area linked to the processing of social pain) during ostracism in a Cyberball game (Eisenberger, Lieberman, & Williams, 2004), a more recent meta-analysis could not confirm this relationship but instead observed reliable activity in the default network (Mwilambwe-Tshilobo & Spreng, 2021), and activation pattern associated with self-referential processes, but also with mind-wandering or daydreaming (Kucyi & Davis, 2014). The present study's failure to detect enhanced vulnerability to ostracism in individuals higher on psychopathology — a proposition drawn from real-life observations (Reinhard et al., 2019) — may be best explained by the overall moderate main effect of ostracism in the present study.

Two possible factors may explain why social stress resulting from ostracism in Cyberball studies may be moderate in comparison to the profound effects of ostracism in everyday life. Firstly, Cyberball studies induce a single and brief episode of ostracism, while ostracism experiences in real life often span over larger time periods (Riva et al., 2016). Secondly, it cannot be ruled out that ostracism from artificial agents represent a milder stressor compared to ostracism from humans. A small number of previous studies did compare ostracism from artificial agents and humans and found overall similar effects (Jauch et al., 2022;

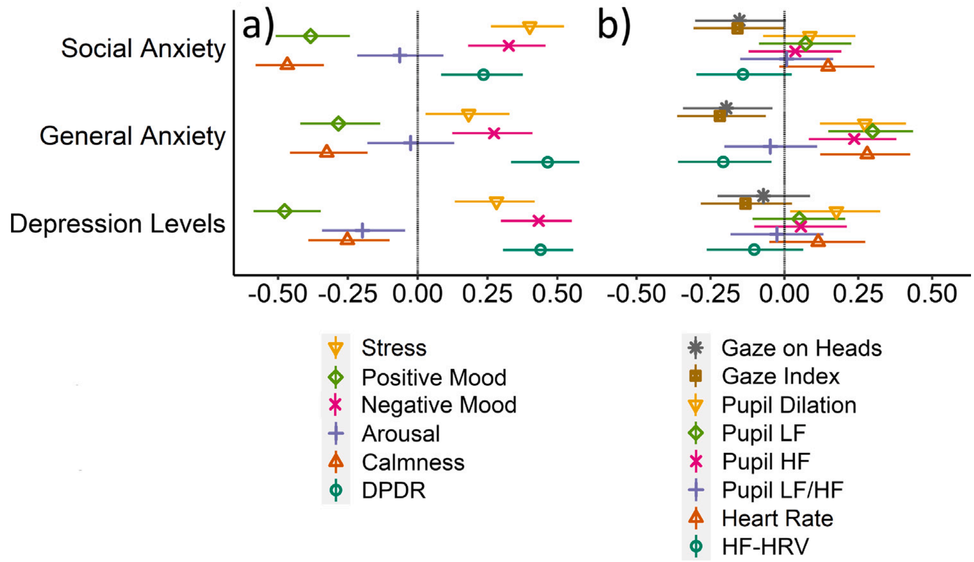

Fig. 5. Correlations between social anxiety, general anxiety and depression levels with (a) subjective and (b) objective measures. Lines represent 95%-CIs.

Kothgassner et al., 2014; Zadro et al., 2004), but focused mainly on the above-mentioned and potentially problematic need-threat scale and did not directly compare effects resulting from a Cyberball game with effects of real-life ostracism. More generally, it remains unclear to what extent reactions to artificial agents resemble reactions towards humans. Several studies observed similarities in short-term physiological and cognitive reactions to interacting with artificial agents and interacting with humans (Caruana, Brock, & Woolgar, 2015; Kompatsiari, Bossi, & Wykowska, 2021; Schilbach et al., 2010; Wienrich, Gross, Kretschmer, & Muller-Plath, 2018) and even found enhanced trust towards chatbots which used an empathic language (Pelau, Dabija, & Ene, 2021). The avoidance of gaze contact in individuals who were high on psychopathology in the present study — a behavior which was originally observed in interactions between humans — likewise speaks to the idea of similar reactions towards artificial agents and towards humans. On the other hand, artificial agents are typically not ascribed a capability for own experiences (Gray, Gray, & Wegner, 2007; Rosenthal von der Pütten, Krämer, Hoffmann, Sobieraj, & Eimler, 2013), possibly explaining why people reported low levels of personal attachment to a commercial chatbots (Lee, Kavya, & Lasser, 2021). Note that comparisons between attitudes towards artificial agents and humans may additionally need to be viewed through a historic perspective since it was observed that social presence experienced in response to artificial agents diminished throughout the last decades despite advances in their behavioral realism (Oh, Bailenson, & Welch, 2018). Therefore, although some researchers express optimism that humans may at some point form friendships with artificial agents (Ho, Hancock, & Miner, 2018), future research may likewise observe that the fundamental human need for long-term interpersonal bonds (Baumeister & Leary, 2017) remains to be best met by other humans.

An additional methodological problem which complicates the quantification of effects resulting from ostracism in Cyberball studies is a widespread use of a deceitful cover story where participants are informed that other agents were being controlled by humans when they are in fact computer-controlled. Among the few studies which explicitly tested belief in this cover story, Davidson et al. (2019) found that 71% of participants harbored suspicions against the cover story and participants in a study by Kothgassner et al. (2021) on average rated the likelihood to actually having played with an artificial agent to be more than 7 on a scale from 0 to 9. With overall lacking belief in the cover story, reactions to ostracism in a Cyberball game may contain reactions to detecting deceit (Walczyk & Newman, 2020). Moreover, the use of deceit makes it difficult to interpret both similarities between ostracism from artificial agents and alleged humans (since participants in both conditions are aware of playing with artificial agents) and differences (since only participants in one condition experience being deceived). Similarly as in other areas of psychological experimentation, deceit in Cyberball studies results in ethical and methodological problems (Hertwig & Ortmann, 2008; Kelman, 2017).

Correlations between psychopathology and overall levels of stress and mood are not surprising and even partly tautological since alterations in stress levels and mood can be understood as an expressions of psychopathology (Watson & Naragon-Gainey, 2014). We nonetheless find it interesting to note that the effect of underlying psychopathology substantially exceeds the effect of experiencing ostracism in a Cyberball game on these subjective measures, highlighting the robust effects of long-term habitual modes of experience in comparison to brief experimentally induced experiences.

In addition, psychopathology was also associated with several objective markers of social stress. Reduced eye gaze on agents' heads may be interpreted to mirror stress in social situations (Vatheuer et al., 2021) which is enhanced in psychopathology (Redcay & Schilbach, 2019; Schilbach, 2016). Stress in reaction to social situations may likewise explain correlations between psychopathology and pupil size measures (Hepsomali et al., 2017), heart rate (Vrijkotte et al., 2000) and HF-HRV (Shaffer & Ginsberg, 2017) observed in the present study. The present study did not confirm a particularly close tie between social anxiety and stress in social situations which may be expected from the phenomenology of social anxiety (Morrison & Heimberg, 2013) but instead observed similar patterns for social anxiety, general anxiety and depression levels, with effects on objective markers overall highest for general anxiety. Together with factor-analytical evidence for a substantial overlap of different measures of psychopathology, this observation confirms the importance of general psychopathology as a parsimonious description of inter-individual variation in clinical psychology (Caspi & Moffitt, 2018; Kotov et al., 2021).

From a practical perspective, the finding that psychopathology levels can be inferred to some extent from data streams which are collected and processed automatically when people use social VR may pave the way for novel screening tools. On the other hand, this finding also highlights a profound risk to data security. While previous research demonstrated that users' age, gender, handedness or room size could be inferred from data streams left behind in social VR (Wang et al., 2023), psychopathology levels represent particularly sensitive personal data which deserve protection. Although only few commercially available head-mounted displays (HMDs) can collect heart rate, an integration of eye-tracking devices is becoming more widespread, making gaze and pupil size data from a larger number of users easily accessible. Eye gaze data may be a particularly rich source of information on people's psychopathology or personality levels as they allow to more closely delineate reactions to different objects or individuals such as an avoidance of eye contact specifically with higher ranked people (Gobel, Kim, & Richardson, 2015). Social VR users may choose to use only trustworthy platforms with appropriate data security policies. Future research should assess further what inferences can be drawn from automatically collected data streams in such environments. Researchers, but also developers of educational and recreational games should be aware that these data may contain sensitive personal information and should be collected, stored and analyzed only when participants and users have expressed their informed consent. On the other hand, since ostracism from artificial agents was observed to only mildly stress participants, designers of such games may implement a wider range of behavior in artificial agents (i.e., actions which could be considered impolite in real-world situations) without causing substantial social pain in users. Several fields can profit from confronting participants with a wide rang of behavioral patterns in artificial agents, as when social behavior is practiced across a range of situations in a virtual social skills training (Howard & Gutworth, 2020).

4.1. Limitations

The present study observed a correlation between psychopathology levels and subjective as well as objective markers of social stress in an interaction with artificial agents in VR, but cannot unequivocally attribute findings to individual elements of the testing situation. For instance, heightened heart rate may be a result of interacting with an artificial agent, but could also result from the experimenter's presence in the room or the mere demands associated with being a participant in a research study. It is difficult to estimate the origin of observed effects based on previous studies where such factors are likewise conflated. For instance, while Rösler et al. (2021) found a positive correlation between social anxiety symptoms and heart rate during a social interaction, Pittig et al. (2013) found no relationship with heart rate and any form of anxiety, but a negative correlation between HF-HRV and anxiety symptoms in patients assessed at rest in a University laboratory. By contrast, Sperry, Kwapil, Eddington, and Silvia (2018) found a trend towards reduced heart rate and heightened heart-rate variability in anxiety during an ambulatory assessment. Whereas Rubo and Gamer (2020) found correlations between social anxiety levels and social gaze only in a live situation but not during passive viewing of a social situation on a computer monitor, other studies such as Moukheiber et al. (2010), Chen, Thomas, Clarke, Hickie, and Guastella (2015) and Rubo et al. (2023) observed reduced gaze at people's faces in social anxiety during passive viewing. However, while participants in the study by Rubo and Gamer (2020) where alone in a testing booth during passive viewing, participants in the study by Chen et al. (2015) were being filmed and evaluated by another person and in the studies by Moukheiber et al. (2010) and Rubo et al. (2023), it remains unclear if participants were alone in a room or in the presence of another person.

Participants in the present study were recruited at a university in Switzerland, thus constituting a convenience sample which may in several ways not be representative of the general population in several ways, especially not for the population in other cultures (Henrich, Heine, & Norenzayan, 2010). It may nonetheless be said that a seeking of social interactions was observed to be universal motivation in humans (Baumeister & Leary, 2017), suggesting that findings regarding ostracism in the present study may not be limited to student populations in particular. In addition, the distribution of personality and psychopathology variables in the present sample were comparable to those of a wider population (Byrow et al., 2016; Hinz et al., 2016; Rubo et al., 2023), indicating that findings regarding these variables may likewise not be limited to students. Overall moderate levels of psychopathology in the present study may have contributed to a low discriminability of individual facets of psychopathology, although it must be noted that the p factor is also observed in clinical samples (Kotov et al., 2021). Additionally, participants in the present study were only characterized along a small set of psychological scales and we used short forms for the assessment of personality, general anxiety and depression levels, relying on a total of only 34 items. Although we did assess the most common forms of psychopathology (Kroenke et al., 2009), note that in comparison, participants in a study by Wendt et al. (2022) responded to a total of 685 items in order to allow for a comprehensive assessment of psychopathology. While it was nonetheless possible to detect a distinct p factor among these scales, future research should incorporate a larger set of measures for psychopathology to more clearly characterize individual facets.

In installing a body illusion in VR, we used a relatively simple and cheap approach to align a virtual body's posture with the posture of a participant: Based only on head and hand positions and orientations, all other joints were set using an inverse kinematics (IK) algorithm. Compared with a more thorough tracking of a larger number of body joints, the use of IK algorithms generally poses a risk of misaligning body joints such as the shoulders and elbows which are only inferred but not tracked. We therefore used an IK algorithm which is specifically designed for VR body illusions and has been employed in other research and commercial applications (http://root-motion.com/). The algorithm conservatively assumes elbows to be pointing downwards, thus avoiding unwanted jittering and creating a believable body posture in people who are standing, gesturing or catching and throwing a ball. While we did not observe any unwanted side effects of using IK algorithms in creating a body illusions, future studies may additionally track other body parts and improve the mapping of the virtual and real bodies' postures.

4.2. Conclusion

We assessed subjective and objective markers of social stress in response to ostracism from artificial agents in VR, but also as a function of underlying psychopathology levels. Overall moderate effects of ostracism in a Cyberball game add to mounting evidence that the paradigm may not be a strong stressor, suggesting that future research may more systematically compare effects of a Cyberball game with ostracism experiences in everyday life. By contrast, underlying psychopathology levels were not only associated with alterations in stress and mood levels, but also with reduced gaze at artificial agents' heads, larger pupil size, higher heart rate and reduced high-frequency heart-rate variability. Effects were similar across three individual facets of psychopathology (social anxiety, general anxiety, depression levels), with overall largest effects on objective markers for general anxiety. An inclusion of individuals who are more strongly debilitated by individual forms of psychopathology (e.g., patients suffering from SAD or a different anxiety or depressive disorder) is needed to clarify if objective stress markers are best understood as expression of general psychopathology or may be more closely linked to an individual facet of psychopathology. From a practical perspective, this observation shows that psychopathology levels can be inferred based on data which are automatically collected in Social VR applications and highlights the need for robust data security strategies in such environments.

CRediT authorship contribution statement

Marius Rubo: Conceptualization, Software, Formal Analysis, Visualization, Writing – original draft, Writing – review & editing. **Simone Munsch:** Conceptualization, Project administration, Writing – review & editing.

Declaration of competing interest

The authors declare no competing interests.

Data availability

have shared a link to a public data repository.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.chb.2023.107915.

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