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# Finding a positive me: Affective and neural insights into the challenges of positive autobiographical memory reliving in borderline personality disorder

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ABSTRACT

*Background:* This study aimed to investigate whether people with borderline personality disorder (BPD) can benefit from reliving positive autobiographical memories in terms of mood and state self-esteem and elucidate the neural processes supporting optimal memory reliving. Particularly the role of vividness and brain areas involved in autonoetic consciousness were studied, as key factors involved in improving mood and state self-esteem by positive memory reliving.

*Methods:* Women with BPD (N = 25), Healthy Controls (HC, N = 33) and controls with Low Self-Esteem (LSE, N = 22) relived four neutral and four positive autobiographical memories in an MRI scanner. After reliving each memory mood and vividness was rated. State self-esteem was assessed before and after the Reliving Autobiographical Memories (RAM) task.

*Results:* Overall, mood and state self-esteem were lower in participants with BPD compared to HC and LSE, but both the BPD and LSE group improved significantly after positive memory reliving. Moreover, participants with BPD indicated that they relived their memories with less vividness than HC but not LSE, regardless of valence. When reliving (vs reading) memories, participants with BPD showed increased precuneus and lingual gyrus activation compared to HC but not LSE, which was inversely related to vividness.

*Discussion:* Women with BPD seem to experience more challenges in reliving neutral and positive autobiographical memories with lower vividness and less deactivated precuneus potentially indicating altered autonoetic consciousness. Nevertheless, participants with BPD do benefit in mood and self-esteem from reliving positive memories. These findings underline the potential of positive autobiographical memory reliving and suggest that interventions may be further shaped to improve mood and strengthen self-views in people with BPD.

## 1. Introduction

The remembering of our past, i.e. autobiographical memory, supports identity construal, emotion regulation, and social functioning, which are core to the dysfunctions experienced by people with Borderline Personality Disorder (BPD) (Bluck, Alea, Habermas, & Rubin, 2005; Lieb, Zanarini, Schmahl, Linehan, & Bohus, 2004). In the therapeutic setting, the autobiographical memories (AM's) that are shared by patients commonly entail negative and traumatic experiences (Loughead et al., 2010). Focusing on memories of positive experiences may foster positive self-evaluations and support emotion regulation (Korrelboom, Marissen, & van Assendelft, 2011). Detailed knowledge of positive AM reliving in people with BPD therefore is valuable for shaping interventions. However, to the best of our knowledge, no studies to date have investigated the details of positive AM reliving by people with BPD, and there is a clear need to better understand the cognitive

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and neural processes that facilitate or obstruct memory reliving in people with BPD. In this study, we aim to investigate whether people with BPD can benefit from reliving positive autobiographical memories in terms of mood and state self-esteem and which neural mechanisms support optimal memory reliving.

Memories that are not in line with how the self is currently perceived are relived in a more distant manner (Libby & Eibach, 2011). For example, people with high self-esteem were better able to regulate negative mood by recalling positive memories whereas people with low self-esteem were less likely to recall positive memories. (Smith & Petty, 1995). Hence, as people with BPD have more negative self-views (Van Schie, Chiu, Rombouts, Heiser, & Elzinga, 2020; Zeigler-Hill & Abraham, 2006), this may interfere with positive memory retrieval (Conway & Pleydell-Pearce, 2000; Korrelboom et al., 2011; Prebble, Addis, & Tippett, 2013). That is, people with BPD may relive positive memories in a more neutral and more distant way (Libby & Eibach, 2011; Philippe, Lecours, & Beaulieu-Pelletier, 2009). Moreover, in people with BPD, it has been observed that they rate past autobiographical experiences as more negative than at the time the event took place (Carter & Grenyer, 2012; Ebner-Priemer et al., 2006; Jorgensen et al., 2012; Renneberg, Theobald, Nobs, & Weisbrod, 2005; Rosenbach & Renneberg, 2015). Consequently, people with BPD might have more difficulty recalling positive memories as these are not central to the self and spontaneous retrieval of memories may be more negative. These studies indicate that additional aids, such as structured instructions and specific cues may be required to induce mood elevation via the reliving of (positive) memories (Korrelboom, 2011; Pillemer, 2003). Further clarifying what mechanisms may facilitate or obstruct memory reliving is pivotal for the design of an effective memory-based intervention.

Vividness, the degree to which memories are relived with sensory experiences (usually a vivid visual image), seems crucial for positive memories to have an emotional benefit (Engelhard, van Uijen, & van den Hout, 2010; Habermas & Diel, 2013; Suardi, Sotgiu, Costa, Cauda, & Rusconi, 2016). Memories that are relived less vividly are not re-experienced with the same emotional intensity as vivid memories (Philippe et al., 2009; Van Schie, Chiu, Rombouts, Heiser, & Elzinga, 2019). The vivid reliving of memories can be achieved by higher autonoetic consciousness (i.e. awareness of the self in another time) (Holmes, Mathews, Dalgleish, & Mackintosh, 2006; Pillemer, 2003). Two processes of autonoetic consciousness can be distinguished i.e., prereflective and reflective awareness (Prebble et al., 2013). Prereflective awareness, indicates that one is re-experiencing the past event as if it were a present moment (Prebble et al., 2013). Some of the key brain areas for prereflective awareness are the ventral medial prefrontal cortex (mPFC) (Esslen, Metzler, Pascual-Marqui, & Jancke, 2008; Levine, 2004; Speer, Bhanji, & Delgado, 2014), insula (Craig, 2011; Prebble et al., 2013) and medial-temporal lobe (MTL; hippocampus and amygdala in particular) (Judd, 2005; Marceau, Meuldijk, Townsend, Solowij, & Grenyer, 2018; Ruocco, Amirthavasagam, Choi-Kain, & McMain, 2013). Conversely, reflective awareness indicates a meta-conscious experience where one takes more distance from the memory (Libby & Eibach, 2002; Prebble et al., 2013). Within self-referential processes, the precuneus is thought to be involved in linking self-relevant experiences in time and the precuneus as well as the Temporo-Parietal Junction (TPJ) may be relevant in creating more distance from the memory e.g. through third person perspective taking (Grol, Vingerhoets, & De Raedt, 2017; Northoff et al., 2006; Peer, Salomon, Goldberg, Blanke, & Arzy, 2015; St Jacques, Szpunar, & Schacter, 2017).

Whereas little is known about the neural processes involved in the reliving of positive AM in people with BPD, several neuroimaging studies investigated how they relive traumatic AM. During the reliving of traumatic memories, alterations in neural activation have been observed in the insula, orbitofrontal cortex, cuneus and middle occipital cortex in people with BPD (Beblo et al., 2006; Schmahl et al., 2003, 2004; Schnell, Dietrich, Schnitker, Daumann, & Herpertz, 2007). These studies suggest that disturbances in AM reliving in people with BPD may relate to disturbed emotion regulation and self-referential processing (Beblo et al., 2006; Schmahl et al., 2003; Schmahl et al., 2004; Schnell et al., 2007). Studying self-referential processes during *positive* memory reliving is an important next step. Studies have shown clinical benefits of memory-based interventions for people with low self-esteem and affective and personality disorders, including BPD (Hitchcock, Werner-Seidler, Blackwell, & Dalgleish, 2017; Korrelboom et al., 2011) (Jacob et al., 2011). However, given prevailing negative self-views, it may be more challenging for people with BPD to engage fully and vividly with positive memories and may have less of an uplifting effect on current mood and self-evaluations. Neurally, this may be expressed through less prereflective awareness (e.g. differential activation in mPFC and MTL) and/or more reflective awareness (e.g. differential activation in precuneus and TPJ).

Of note, negative self-views are not unique to BPD. Other research has shown that autobiographical memory functioning in people with BPD, such as overgeneral memories, i.e. not set in a specific time and location (Van den Broeck, Claes, Pieters, Hermans, & Raes, 2015), may be explained by comorbid depression (Arntz, Meeren, & Wessel, 2002; Reid & Startup, 2010). Therefore, we included a comparison group consisting of individuals with overall negative self-views and similar rates of depression psychopathology in this study, which can yield valuable information on the specificity of these processes to people with BPD. It should be further noted that women and men appear to differ in the way they recall autobiographical memories and in the neural correlates underlying reliving (Grysman, Fivush, Merrill, & Graci, 2016; Spets & Slotnick, 2021; Young, Bodurka, & Drevets, 2017). To be able to draw meaningful conclusions we therefore limited our investigation to women only.

This study sought to investigate the impact of positive autobiographical memory reliving on mood and self-esteem in women with BPD and how memory vividness and underlying neural processes facilitate or obstruct memory reliving in women with BPD. To facilitate memory reliving, participants wrote down memories to be presented as cues and were instructed on memory specificity, word count and first-person perspective taking. Participants were asked to read and then relive their memory creating two conditions in which participants engage with their memory through either constructing (reading) or reliving. Contrasting reliving to reading the memory allows for understanding whether and how groups may differently engage with the experience of the remembered episodes that may indicate a lower level of self-relevancy similar to when reading the memory without elaborating on somatosensory experiences. Moreover, other memory characteristics and the ability to use imagery were measured. Specifically, we compare groups on the degree to which they use imagery in their daily life and on the remoteness of the memories. In addition, to have an understanding of the memory content we described occurrence of prototypical life events and social context in which the memory took place. Women with BPD were compared to non-clinical controls and to a control group with low self-esteem, to differentiate which results are specific to women with BPD and which could be ascribed to low trait self-esteem. We hypothesized that women with BPD 1) report a more positive mood when reliving positive memories compared to neutral memories and higher state self-esteem after reliving memories compared to before and compare these effects to a non-clinical and low self-esteem control group, 2) show reduced vividness when reliving positive memories compared to neutral memories, compared to non-clinical and low self-esteem controls, and 3) show differences in activation in the neural networks involved in prereflective awareness (e.g. mPFC, MTL) and/or reflective awareness (e.g. precuneus, TPJ) indicative of more distant reliving compared to a non-clinical and low self-esteem control group.

## 2. Methods and materials

### 2.1. Participants

Participants (N = 80, all female, Age $M = 29.76$, $SD = 9.3$, $R = 18–54$ years) consisted of people diagnosed with Borderline Personality Disorder (BPD group: $N = 25$), Healthy Controls (HC group: $N = 33$), and Low Self-Esteem controls (LSE group: $N = 22$). The LSE group (M = 12.73, SD = 2.9) and the BPD group (M = 11.33, SD = 6.2) did not differ in their overall trait self-esteem (i.e. as measured with Rosenberg Self-Esteem Scale (RSES)). As expected, both the BPD and LSE group had lower trait self-esteem than HC ($M = 23.76$, $SD = 3.2$), see Table 1. HC and LSE were matched on gender, age, education level and handedness (van Strien, 1992) to individuals with BPD. Despite careful matching efforts, HC (but not LSE) had a higher education level than individuals with BPD, see Table 1.

Exclusion criteria for all participants were incompatibility with the MRI scanner, and usage of benzodiazepines (equivalent of >20 mg of Oxazepam) or antipsychotics. Any other medication use (see Table S1) was taken into account. Additional exclusion criteria for HC were any current axis I or axis II disorder. Additional exclusion criteria for LSE were: A diagnosis of BPD (as low self-esteem is a common correlate of psychopathology other current axis I and II disorders were allowed (Zeigler-Hill, 2011)) and RSES score higher than 18 (i.e. cut-off at 1SD below the mean of the Dutch population (Korrelboom, 2011; Schmitt & Allik, 2005)). HC and LSE participants were recruited from the general population where LSE were specifically targeted with adverts seeking insecure individuals. People with BPD were recruited from a mental health institution (GGZ Rivierduinen). Participants were recruited between March 2013 and March 2016. Based on effect sizes and number of participants in previous fMRI studies using similar designs (Eisenberger, Inagaki, Muscatell, Byrne Haltom, & Leary, 2011; Krause-Utz et al., 2014; Sabatinelli, Lang, Bradley, & Flaisch, 2006), the target number of participants per group was set to 30 with 30% oversampling to allow for dropout and data loss. From 34 HC, one participant was excluded from analyses because of scanner artefacts. From 38 participants with BPD, 10 participants dropped out after the first assessment session and hence did not complete the scan component. Three participants with BPD were further excluded, due to scanner artefacts (1) neural abnormalities (1) and excessive head motion (>6 mm) (1). Due to time constraints the LSE recruitment resulted in 24 participants with two participants not completing the scan component, resulting in the final sample of 80 participants.

The study was approved by the medical ethics committee of the Leiden University Medical Center (P12.249) and conducted in accordance with the Helsinki Declaration of 1975, as revised in 2008 and the Dutch Medical Research Involving Human Subjects Act (WMO). A validation of the task in a subsample of participants without current psychological disorders and their responses to the reliving autobiographical memories task has previously been described in Van Schie et al. (2019). The current study focuses on how people with BPD relive positive autobiographical memories as compared to two control groups.

**Table 1**
Demographics of sample ($N = 80$) by group.

| | HC ($N = 33$) | LSE ($N = 22$) | BPD ($N = 25$) | Comparison |
|---|---|---|---|---|
| Variable | Mean (*SD*)<br>Count (%) | Mean (*SD*)<br>Count (%) | Mean (*SD*)<br>Count (%) | |
| Age (years) | 28.18 (9.6) | 31.91 (8.9) | 29.96 (9.4) | $F(2,77) = 1.08$, $p = .345$ |
| Education level[a] | | | | $\chi^2(2) = 7.36$, $p = .025$<br>HC = LSE, LSE = BPD, HC > BPD |
| - High School | 1 (3.0%) | 4 (18.2%) | 7 (28.0%) | |
| -Vocational training (MBO) | 20 (60.6%) | 7 (31.8%) | 14 (56.0%) | |
| -Higher education (HBO & University) | 12 (36.4%) | 11 (50.0%) | 4 (16.0%) | |
| Handedness | 8.15 (4.9) | 8.33 (4.7) | 7.28 (6.3) | $F(2,76) = 0.27$, $p = .762$ |
| -Right handed (8+) | 28 (87.5%) | 19 (90.4%) | 22 (84.6%) | |
| -Left handed (−8+) | 1 (3.1%) | 1 (4.8%) | 3 (11.5%) | |
| -Ambidextrous (-7-7) | 3 (9.4%) | 1 (4.8%) | 1 (3.9%) | |
| Trait self-esteem (RSES) | 23.76 (3.1) | 12.73 (2.9) | 11.33 (6.2) | $F(2,76) = 74.75$, $p < .001$<br>HC>LSE = BPD |
| Imagery ability (SUIS) | 36.42 (10.25) | 36.82 (9.27) | 39.08 (13.00) | $F(2,77) = 1.30$, $p = .279$ |
| Axis I disorder (DSM-IV) *(frequency of current/lifetime(incl. current))* | | | | |
| -Mood disorders | 0/3 | 5/11 | 6/15 | |
| o MDD | 0/3 | 4/10 | 5/13 | |
| oDysthymia | 0/0 | 1/1 | 1/2 | |
| -Anxiety disorders | 0/2 | 5/6 | 7/9 | |
| oPanic Disorder | 0/1 | 0/0 | 2/4 | |
| oAgoraphobia | 0/1 | 0/0 | 1/1 | |
| oSocial Phobia | 0/0 | 3/3 | 1/1 | |
| oSpecific Phobia | 0/0 | 0/0 | 1/1 | |
| oOCD | 0/0 | 0/1 | 0/0 | |
| oGAD | 0/0 | 2/2 | 2/2 | |
| -PTSD | 0/1 | 0/0 | 2/2 | |
| -ADHD | 0/0 | 2/2 | 5/5 | |
| -Substance abuse & addiction | 0/0 | 0/0 | 5/6 | |
| oAlcohol | 0/0 | 0/0 | 2/2 | |
| oDrugs | 0/0 | 0/0 | 3/4 | |
| -Other disorders | 0/0 | 4/7 | 1/1 | |
| Borderline symptoms | | | | |
| -VKP-BPD (Questionnaire for Personality traits) | 1.31 (1.6) | 7.48 (3.9) | – | |
| -BPD-Severity Interview | – | – | 30.14 (9.9) | |
| Axis II disorders (DSM-IV) | | | | |
| -Borderline | – | – | 26 | |
| -Antisocial | – | – | 1 | |

[a] Group differences in education level were assessed using a Kruskal Wallis test followed by three Wilcoxon rank sum tests (Bonferroni corrected).

### 2.2. Procedure

After phone screening, participants were seen twice. During the first appointment, participants signed informed consent, filled in a demographic form and questionnaires, and wrote down four positive and four neutral autobiographical memories. During the second appointment, participants performed the 'Reliving Autobiographical Memories' (RAM) task in the scanner (after completing a Social Feedback (SF) task as part of a larger neuroimaging study in individuals with BPD (Van Schie et al., 2020)). Individuals with BPD did not differ from HC in days between appointments (*Median BPD* = 5 days, *R* = 0–54), *Median HC* = 1 day, *R* = 0–53) ($t(75) = -0.34$, $p = .936$). Due to practical reasons time between appointments was shorter for LSE (*Median* = 0, *R* = 0–38) than individuals with BPD ($t(75) = -3.08$, $p = .008$). Time between appointments was therefore taken into account in additional statistical sensitivity analyses. Afterwards, outside the scanner, participants filled out questions on their experiences with the RAM task and were debriefed and rewarded (30 euro).

### 2.3. Reliving autobiographical memories task

The 'Reliving Autobiographical Memories' (RAM) task has previously been described in Van Schie et al. (2019). In brief, during the first appointment participants wrote down four neutral and four positive autobiographical memories with the instructions to write down a specific memory with as many details as recalled from a first-person perspective and in the present tense that either made them feel good (positive memories) or did not elicit much emotion (neutral memories). Participants provided a date of the memory (month/year) and rated the pleasantness (range: negative (−10) to positive (+10)).

During the second appointment, while in the scanner, participants relived four neutral memories as the baseline, followed by four positive memories. Participants read their memory on screen (35s) and were then instructed to relive the memory as best as they could while a fixation cross was presented (30s). Each memory was followed by the question how good they felt right now (very bad (1) to very good (4)), how vivid the memory was (not vivid at all (1) to very vivid (4)) and how well they could focus on the memory (very bad (1) to very good (4)).

### 2.4. Measures and materials

#### 2.4.1. Psychopathology

The MINI, a semi structured interview, was used to assess lifetime and current Axis-I disorders based on DSM-IV (First, Spitzer, Gibbon, & Williams, 1997). Individuals with BPD were assessed by a trained psychologist as part of their intake and diagnosis at the mental health institute. HC and LSE participants were assessed by a trained psychologist (C.v.S).

Personality disorders were assessed using IPDE-IV in individuals with BPD (Loranger, 1999). Borderline symptom severity was assessed using the BPD-SI (Giesen-Bloo, Wachters, Schouten, & Arntz, 2010). HC and LSE were screened for personality disorders using the SAPAS-SR (Germans, van Heck, Moran, & Hodiamont, 2008). A score of four or greater indicates the likelihood of a personality disorder and led to exclusion in the HC group. As axis I and II psychopathology was allowed in the LSE group, except for a diagnosis of BPD, individuals with a score >4 were followed-up with a structured interview with the SCID-II to exclude a diagnosis of BPD before inclusion (First, Gibbon, Spitzer, Williams, & Benjamin, 2000). Furthermore, the level of borderline symptoms were assessed in both HC and LSE using the BPD items of the VKP ('Questionnaire for Personality Traits') (Duijsens, Eurelings-Bontekoe, & Diekstra, 1996)).

#### 2.4.2. Trait self-esteem (RSES)

The Rosenberg Self-Esteem Scale was used to assess trait self-esteem. The scale consists of 10 items rated on a four-point scale ranging from totally disagree (0) to totally agree (3). The sum of the items was used to represent trait self-esteem. The validity and reliability of the scale has been established (Gray-Little, Williams, & Hancock, 1997; Schmitt & Allik, 2005). The internal consistency was good (Cronbach alpha = 0.93).

#### 2.4.3. State self-esteem

State self-esteem was assessed at baseline (before entering the MRI scanner), and before and after the Social Feedback (SF) task and the Reliving Autobiographical Memory (RAM) task. Participants answered the question "How good do you feel about yourself right now?" on a scale ranging from 'very bad – worst I have ever felt about myself' (0) to 'very good – best I have ever felt about myself' (100).

#### 2.4.4. Memory and reliving phenomenology

Memory content was coded for specificity, event type and social context by four trained raters in pairs (forming four pairs), who were blind to group membership and valence. For specificity, the standard categories of the Autobiographical Memory Task were used (i.e., specific, extended and categoric) (Williams & Broadbent, 1986). Category descriptions of event type (major life event, minor life event, routine activities) and social context (i.e., partner, family, friends, colleagues, alone), can be found in Table S2. All memories were double rated and conflicting labels were resolved through discussion with an independent rater (CvS or BE). The interrater agreement was good for the four pairs of raters for specificity [86%–94%], event type [81%–87%], and social context [80%–86%]. Individuals with BPD were compared to HC and LSE on the following memory characteristics pleasantness, remoteness in months, word count, specificity, event type, social context, and level of focus during reliving. Using multilevel models we tested for each of these memory characteristics whether 1) the main effect of valence (neutral and positive) was a significant addition compared to the null model (intercept only model), 2) the main effect of group (BPD group as reference) was a significant addition compared to the model with valence only and 3) the valence by group interaction was a significant addition compared to the model with main effects only. These models were compared using a chi-square test as log likelihood test within the lme4 package in R (see further details under Data analysis). The distribution of memory type among groups for specificity, event type and social context, was analysed using a chi-square test. Furthermore, groups were compared with a one-way ANOVA on the frequency of using imagery in daily life using the Spontaneous Use of Imagery Scale (SUIS) (Nelis, Holmes, Griffith, & Raes, 2014; Reisberg, Pearson, & Kosslyn, 2003). The internal consistency of the SUIS in the current sample was good (Cronbach's alpha = 0.84). Finally, groups were compared with a one-way ANOVA on their overall perspective taking during reliving, which was assessed outside the scanner as "To what extent did you relive memories from the perspective of 'looking down at myself' (third person perspective (0)) and/or 'looking through my own eyes' (first person perspective (100)).

### 2.5. Data acquisition

Affective ratings were recorded during the scan in E-prime version 2.0 using button boxes operated by left and right index and middle finger. MRI images were acquired using a Phillips 3.0 T scanner equipped with a SENSE-8 channel head coil and situated at the Leiden University Medical Center (LUMC). A survey scan was used to set the scan surface. During the RAM task, T2*-weighted echo planar imaging (EPI) was used with the following parameters: FOV RL: 220 mm, AP: 220 mm, FH: 114.68 mm; Matrix 80 × 80, Voxel size RL: 2.75 mm AP: 2.75 mm; Slice thickness: 2.75 mm; Interslice skip: 0.275 mm; 38 transverse slices in descending order; TE: 30 ms, TR: 2200 ms, Flip Angle: 80°. As the RAM task was self-paced, number of volumes varied ($M = 305.84$, $SD = 9.63$) but did not differ between groups ($F(2,77) = 2.23$, $p = .114$). For registration purposes a four-volume high resolution T2 weighted EPI

and a structural 3D T1 weighted scan were acquired. The parameters for the T2 weighted scan were: FOV RL: 220 mm, AP: 220 mm, FH: 168 mm; Matrix 112 × 112, Voxel size RL: 1.96 mm AP: 1.96 mm; Slice thickness 2.0 mm; 84 transverse slices; TE 30 ms, TR 2200 ms, Flip Angle 80°. The parameters for the 3D T1 scan were: FOV RL: 177.33 mm, AP: 224 mm, FH: 168 mm; Matrix 256 × 256, Voxel size RL: 0.88 mm AP: 0.87 mm; Slice thickness 1.20 mm; 140 transverse slices; TE 4.6 ms, TR 9.7 ms, Flip Angle 8°; Duration 4:55 min.

### 2.6. Data preprocessing

Raw e-prime data were pre-processed in excel 2010 to calculate onset and duration times and recode responses. Raw fMRI data were pre-processed using Feat v6.00 in FSL 5.0.7. The first 5 volumes were discarded. A high pass filter of 120s was used. Motion was corrected using MCFLIRT with 6 degrees of freedom (dof) and the middle volume as reference volume. No slice time correction was used but temporal derivatives were added in the model. Data were spatially smoothed with FWHM of 5 mm. Raw and pre-processed data were checked for quality, registration and movement. Most participants (N = 71, 89%) showed minimal motion (i.e., smaller than 1 voxel/3 mm). For nine participants ($N_{HC} = 2$, $N_{LSE} = 3$, $N_{BPD} = 4$) who showed motion between 1 and 2 voxels (i.e., 3–6 mm), volumes with large motion were regressed out by adding confound regressors (one per large motion volume) defined by the FSL motion outlier script (metric = root mean square). Mean motion did not differ between groups ($F(2,77) = 2.04$, $p = .137$). The middle volume was registered to the high resolution T2 image using 6 dof. For registration to the anatomical T1 scan, the Boundary-Based Registration algorithm was used. A linear 12 dof transformation was used for registration to the MNI template. In addition, motion parameters (6), and white matter and cerebrospinal fluid (csf) signal (2) were added, resulting in eight confound regressors plus any additional motion outlier regressors.

### 2.7. Data analysis

Our main interest was to compare BPD to HC. To investigate the specificity of results, BPD were also compared to LSE. BPD was therefore set as the reference group to contrast to HC and LSE.

#### 2.7.1. Mood, vividness and state self-esteem

R version 3.5.1 was used with the following packages: lme4 for multilevel analysis, psych for descriptive statistics and ggplot2 for creating figures (Bates, Maechler, Bolker, & Walker, 2015; R Core Team, 2013; Wickham, 2009). We used multilevel analysis with the maximum likelihood estimator to understand whether valence (neutral vs positive) and group (BPD vs HC and LSE) affected mood and vividness after reliving each memory. To test the main effect of valence, main effect of group and the interaction effect of valence by group, we compared increasingly complex models using the chi-square test as a log likelihood test. For each outcome (i.e. mood and vividness), we created four models to test three model comparisons to understand whether 1) adding the main effect of valence is a significant improvement compared to the null model (intercept only model) 2) whether adding the main effect of group is a significant improvement compared to the model with valence only and 3) whether the interaction between group and valence is a significant improvement compared to the model with main effects only. To further understand any main and interaction effects, the model parameters were evaluated with t-tests within the model (out of four models) that fitted the data best. Confidence intervals (95%) for parameters in the model were calculated within the lme4 package with parametric bootstrapping using 7500 simulations and the percentile method. All probability levels were evaluated with $\alpha = 0.05$, two-sided. The neutral valence was set as the reference valence. Vividness ratings were recoded from values 1, 2, 3, 4 to contrast values −3, −1, 1, 3 to contrast less and more vivid memories.

To model change in state self-esteem before to after the RAM task, multilevel analysis was performed testing the main effect of group and time (before RAM and after RAM) as well as their interaction. We created four models to test whether 1) adding the main effect of time improved the model significantly compared to the null model (intercept only model), 2) adding the main effect of group improved the model significantly compared to the model with time, and 3) adding the interaction between group and time improved the model significantly compared to the model with main effects only. In addition, we aimed to check whether groups differed in baseline state self-esteem. Moreover, to check whether any of the effects of the SF task did not affect state self-esteem at the start of the RAM task we compared baseline and before SF state self-esteem levels to before RAM task levels. To this end, we conducted an additional multilevel analysis using the same four models however, including all five time points simultaneously (baseline, before SF, after SF, before RAM, after RAM) and setting before RAM as the reference time point to compare to baseline and before SF.

As a measure of effect on mood, vividness and state self-esteem, we included the standardized parameters (*std.b*) which indicate the change in the outcome variable with a one standard deviation change in the predictor variable. For the overall model we included the variance explained compared to the null model (Cohen's $f^2$) (in accordance with recommendations by Lorah, 2018).

#### 2.7.2. Bold responses

FSL version 5.0.7 was used to analyze bold responses during RAM task. On the first level the onset and duration of reading and reliving each memory was specified for neutral and positive memories separately with equal weighting, resulting in four regressors (i.e. neutral reading, neutral reliving, positive reading, positive reliving). The following contrasts were of interest: 1) reliving vs reading, 2) positive reliving vs neutral reliving.

On the second level, individuals with BPD were compared to HC and to LSE using whole-brain t-tests on both first-level contrasts. For inference on the second level t-contrasts, permutation tests were performed with 5000 permutations and threshold free cluster enhancement (TFCE) using Randomise v2.9 (Winkler, Ridgway, Webster, Smith, & Nichols, 2014). Permutation tests are an adequate way of keeping false positive rates within boundaries (Eklund, Nichols, & Knutsson, 2016). Permutation tests were performed within a grey matter mask based on FSL grey matter priors (cut-off = 63 (25%)) and the resulting p-value maps were evaluated with $\alpha = 0.05$. To illustrate any group differences found, featquery was used to extract the mean parameter estimate (PE) per participant per condition from a significant cluster. These mean parameter estimates per participant were used to calculate the mean and standard deviation of activation per group to plot. The permutation tests indicate whether the BPD group differs from HC and LSE group. In addition, to support interpretation of findings, post-hoc t-tests on PE's were conducted to understand within groups whether activation for reading differed from reliving memories. To this end, we used multi-level analysis (in lme4) where we recreated the model with the effects tested in the fMRI analyses, i.e. the main effect of memory condition (reliving vs reading), the main effect of group (BPD, LSE or HC), the main effect of valence (neutral and positive) and the interaction between memory condition by group. The reading condition was set as the intercept level to which reliving was compared. To derive the estimates per group, the reference level of group was set accordingly.

In addition, an exploratory analysis was run on the relation between memory vividness and bold responses. To this end, a parametric modulation of vividness was conducted on the first level to relate vividness to bold responses i.e. each reliving phase was modulated with the vividness contrast rating (−3, −1, 1, 3) of that particular memory. On the second level, a regression analysis was performed testing the positive and negative relation of vividness with bold responses. Using Randomise v2.9, a one sample *t*-test was performed on the positive and negative relation with vividness, masked by the areas found to distinguish

individuals with BPD from HC in the contrast reliving compared to reading and evaluated with $\alpha = 0.05$ (Winkler et al., 2014).

## 3. Results

### 3.1. Memory and reliving phenomenology

With respect to characteristics of the memories, multilevel analysis indicated that there was no main effect of group on memory pleasantness ($\chi^2(2) = 1.47$, $p = .480$), or on remoteness of the memory ($\chi^2(2) = 1.20$, $p = .549$). However, there was a main effect of group ($\chi^2(2) = 11.37$, $p = .003$) and a valence*group interaction effect ($\chi^2(2) = 9.03$, $p = .011$) on word count indicating that individuals with BPD use fewer words to describe their memories than HC, particularly neutral memories but did not differ from LSE, see Table S3 for all parameters. A chi-square test indicated that event type of memory was not differentially distributed among groups ($\chi^2(8) = 12.77$, $p = .120$). In terms of social context, memories of individuals with BPD less often involved people from a work, sports or school setting compared to HC and more often involved family and friends compared to LSE ($\chi^2(10) = 19.86$, $p = .031$). Moreover, memories of individuals with BPD were more often categorized as non-specific (i.e., categoric and extended) relative to HC but not LSE for both neutral and positive memories ($\chi^2(4) = 35.31$, $p < .001$), see Table S4 for the distribution. With respect to memory reliving, groups did not differ in self-reported use of imagery (SUIS: $F(2,77) = 1.30$, $p = .279$). Throughout the task, groups did not differ in level of focus on reliving ($\chi^2(2) = 2.57$, $p = .277$), nor in overall first-person perspective taking ($F(2,68) = 2.64$, $p = .078$).

### 3.2. Changes in mood and state self-esteem

Memory valence affected mood after each memory ($\chi^2$ (1) = 161.13, $p < .001$). All groups reported a better mood after reliving a positive compared to a neutral memory, ($b = 0.99$, $SE = 0.07$, $t = 13.66$, *95% CI* [0.85, 1.13], *std.b* = 0.35), see Table S5. Group affected mood after each memory ($\chi^2$ (2) = 14.39, $p < .001$). Individuals with BPD reported a lower mood regardless of memory valence compared to HC ($b = 0.97$, $SE = 0.27$, $t = 3.93$, *95% CI* [0.49, 1.44], *std.b* = 0.34) and LSE ($b = 0.69$, $SE = 0.27$, $t = 2.54$, *95% CI* [0.16, 1.22], *std.b* = 0.22). There was no interaction between group and valence on mood ($\chi^2$ (2) = 0.89, $p = .640$) indicating that mood in individuals with BPD increased similarly to HC and LSE in response to positive memories compared to neutral memories, see Fig. 1. The variance explained in mood by valence and group was $R^2 = 0.121$, indicating a medium effect size of Cohen's $f^2 = 0.138$. As groups differed in word count and specificity of memories, we included these variables as potential confounders into the main analyses and found that neither word count ($\chi^2(1) = 1.30$, $p = .254$) nor specificity ($\chi^2(2) = 2.79$, $p = .247$) related to mood.

State self-esteem increased from before to after the RAM task ($\chi^2(1) = 23.23$, $p < .001$), ($b = 15.40$, $SE = 3.09$, $t = 5.00$, *95% CI* [9.30, 21.50], *std.b* = 0.39). Groups differed in state self-esteem ($\chi^2(2) = 24.83$, $p < .001$), such that before the RAM task, individuals with BPD reported a lower state self-esteem than HC ($b = 27.46$, $SE = 4.49$, $t = 6.12$, *95% CI* [18.48, 36.26], *std.b* = 0.68) and LSE ($b = 10.95$, $SE = 4.95$, $t = 2.21$, *95% CI* [0.97, 21.03], *std.b* = 0.24). Moreover, a group by time interaction was found ($\chi^2(2) = 9.32$, $p = .009$) indicating that individuals with BPD increased more in state self-esteem than HC ($b = -12.22$, $SE = 4.09$, $t = -2.98$, *95% CI* [−20.20, −4.08], *std.b* = −0.25) but not LSE ($b = -3.13$, $SE = 4.51$, $t = -0.69$, *95% CI* [−12.04, 5.66], *std.b* = −0.05). The variance explained in state self-esteem by time, group and their interaction was $R^2 = 0.282$, indicating a large effect size of Cohen's $f^2 = 0.393$. In addition, state self-esteem before the RAM task did not differ from baseline ($b = -0.48$, SE = 2.65, $t = -0.18$, *95% CI* [−5.57, 4.70], *std.b* = −0.01) nor from before the SF task ($b = 5.00$, $SE = 2.65$, $t = 1.89$, *95% CI* [−0.11, 10.170], *std.b* = 0.10) indicating that levels of state self-esteem were lower for individuals with BPD throughout the study, but were not affected by the SF task before the RAM task, see Fig. S1.

### 3.3. Vividness of memory reliving

Vividness of each memory was significantly associated with valence,[2] with vividness of neutral memory reliving being lower than positive memory reliving ($\chi^2(1) = 87.66$, $p < .001$), ($b = 0.96$, $SE = 0.10$, $t = 9.74$, *95% CI* [0.77, 1.15], *std.b* = 0.30). On top of valence, there was an effect of group on vividness ($\chi^2$ (2) = 8.04, $p = .018$). Individuals with BPD reported lower vividness of both neutral and positive memories compared to HC ($b = 0.73$, $SE = 0.26$, $t = 2.81$, *95% CI* [0.21, 1.24], *std.b* = 0.22), but not compared to LSE ($b = 0.23$, $SE = 0.29$, $t = 0.82$, *95% CI* [−0.33, 0.79], *std.b* = 0.06), see Table S5. There was no interaction of group by valence on vividness ($\chi^2$ (2) = 0.09, $p = .958$). The variance explained in vividness by valence and group was $R^2 = 0.123$, equating to a medium effect size of Cohen's $f^2 = 0.140$. In addition, neither word count ($\chi^2(1) = 1.47$, $p = .226$) nor specificity ($\chi^2(2) = 4.14$, $p = .126$) related to vividness.

In addition, it was explored whether vividness related to mood after each memory and to changes in state self-esteem from before to after the RAM task. For mood, the main effect of vividness ($\chi^2$ (1) = 31.53, $p < .001$) and the two-way interaction effect of vividness by valence ($\chi^2$ (1) = 17.07, $p < .001$) significantly improved the model. More vivid reliving related to a better mood ($b = 0.08$, $SE = 0.04$, $t = 2.13$, *95% CI* [0.01, 0.15], *std.b* = 0.09), particularly when reliving positive memories ($b = 0.20$, $SE = 0.05$, $t = 4.16$, *95% CI* [0.11, 0.30], *std.b* = 0.20). There was no two-way interaction of vividness by group ($\chi^2$ (2) = 1.13, $p = .567$) nor a three-way interaction of vividness by valence by group ($\chi^2$ (4) = 6.66, $p = .155$) indicating that vividness did not affect mood in groups differently. The variance explained in mood by valence, vividness, group and the interaction of valence by vividness was $R^2 = 0.285$, which equates to a large effect size of Cohen's $f^2 = 0.399$. For state self-esteem, there was no main effect of mean vividness of positive or neutral memories on state self-esteem ($\chi^2$ (2) = 2.69, $p = .260$). However, the two-way interaction of time (before to after RAM task) by mean memory vividness on state self-esteem was significant ($\chi^2$ (2) = 6.75, $p = .034$) indicating that mean vividness for positive memories related to increased state self-esteem after the RAM task ($b = 8.97$, $SE = 3.38$, $t = 2.65$, *95% CI* [2.45, 15.57], *std.b* = 0.78). Mean vividness of neutral memories did not relate to changes in self-esteem ($b = -3.25$, $SE = 2.91$, $t = -1.12$, *95% CI* [−9.04, 2.31], *std.b* = −0.25). There was no three-way interaction of time (before to after RAM task) by group by vividness on state self-esteem ($\chi^2$ (8) = 3.62, $p = .889$) indicating that groups did not differ in how mean vividness of positive or neutral memories related to changes in state self-esteem. The variance explained in state self-esteem by time, group, vividness and the two-way interactions was $R^2 = 0.313$, which equates to a large effect size of Cohen's $f^2 = 0.456$.

### 3.4. Bold responses during memory reliving

A whole-brain one-sample *t*-test per group on the contrast reliving compared to reading memories, revealed activation in neural regions relevant for autobiographical memory, including hippocampus, amygdala, insula, mPFC, ACC and PCC, see Fig. 2 for mean activation per group. This indicates that the reliving compared to the reading condition induced the re-experience of the memory. In this contrast of reliving compared to reading also deactivation was observed in the occipital cortex and precuneus. As a test of our key aim regarding the neural correlates of memory reliving, a whole brain *t*-test comparing individuals with BPD to HC on the contrast reliving compared to reading memories, revealed differential activation in the precuneus, putamen and lingual gyrus, see Table S6. A whole brain *t*-test comparing

[2] However, see supplemental information on learning and emotionality effects on vividness of positive compared to neutral memories.

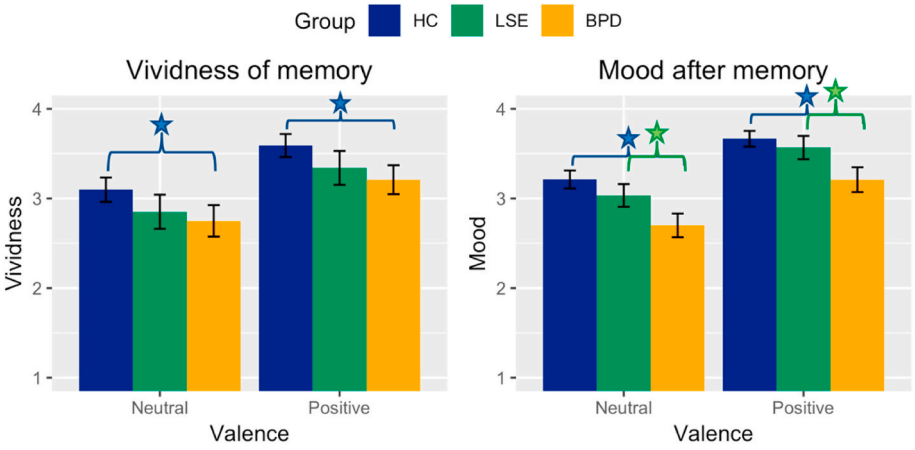


**Fig. 1.** Memory vividness and mood by valence and group. Error bars represent 95% confidence intervals around the mean.

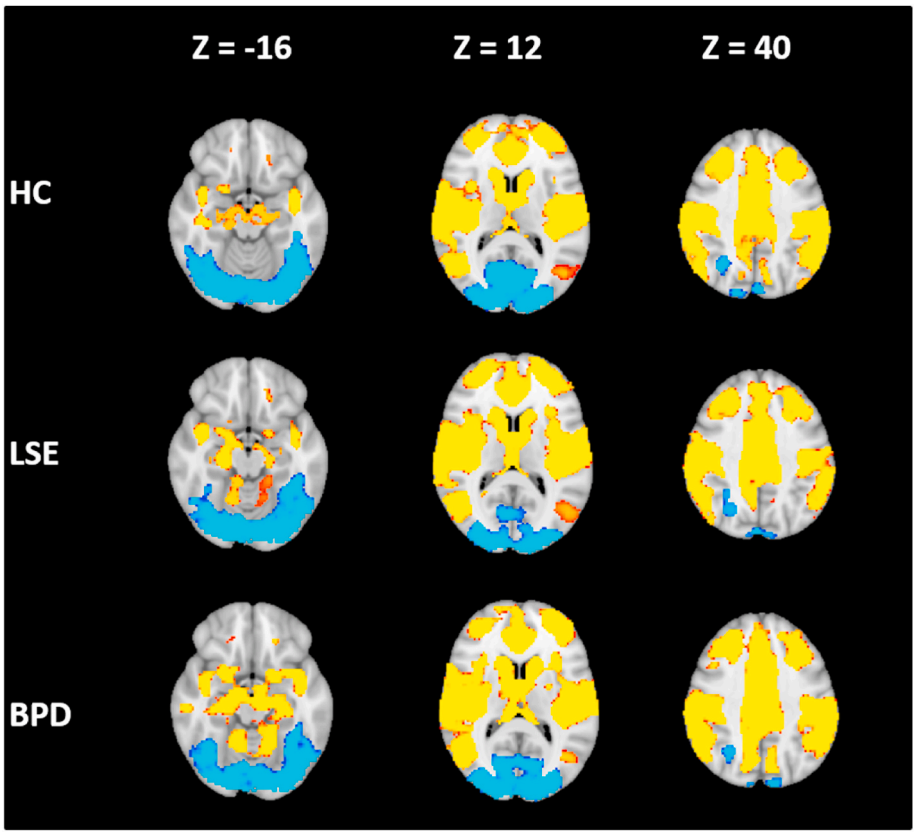


**Fig. 2.** Mean activation (yellow) and deactivation (blue) of reliving compared to reading memories for the HC, LSE and BPD group. Results are based on permutation tests with TFCE correction. Note: brain depicted in radiological convention, i.e. left = right. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

individuals with BPD to LSE revealed no significant differences on the contrast reliving compared to reading memories. To understand how activation differed, post hoc tests with corrected 98%CI were performed on the mean activation for the areas where individuals with BPD differed from HC, precuneus, putamen and lingual gyrus. Mean group activation was plotted for reading and reliving neutral and positive memories separately, see Fig. 3. The activation for LSE was included in the plots and post hoc tests to provide a complete picture.

Post hoc t-tests revealed that for the BPD group, precuneus activation did not differ between reading and reliving memories ($b = 9.92$, $SE = 5.90$, $t = 1.68$, *98% CI* [−3.98, 23.67]), whereas precuneus activation was lower during reliving compared to reading for HC ($b = -51.56$, $SE = 5.13$, $t = -10.04$, *98% CI* [−63.99, −39.88]) and LSE ($b = -20.23$, $SE = 6.29$, $t = -3.22$, *98% CI* [−35.25, −5.55]), see Table S7. Regarding the putamen, individuals with BPD showed higher activation during reliving than reading memories ($b = 19.81$, $SE = 2.76$, $t = 7.19$, *98% CI* [13.44, 26.44]), whereas putamen activation did differ between reading and reliving for both HC ($b = -2.56$, $SE = 2.40$, $t = 1.07$, *98% CI* [−2.93, 8.13]) and LSE ($b = 5.64$, $SE = 2.94$, $t = 1.92$, *98% CI* [−1.26, 12.53]). Regarding activation in the lingual gyrus, the BPD group showed lower activation during reliving compared to reading the memories ($b = -81.82$, $SE = 8.57$, $t = -9.55$, *98% CI* [−102.13, −62.21]). HC also showed lower lingual gyrus activation during reliving compared to reading memories ($b = -159.10$, $SE = 7.46$, $t = -21.33$, *98% CI*

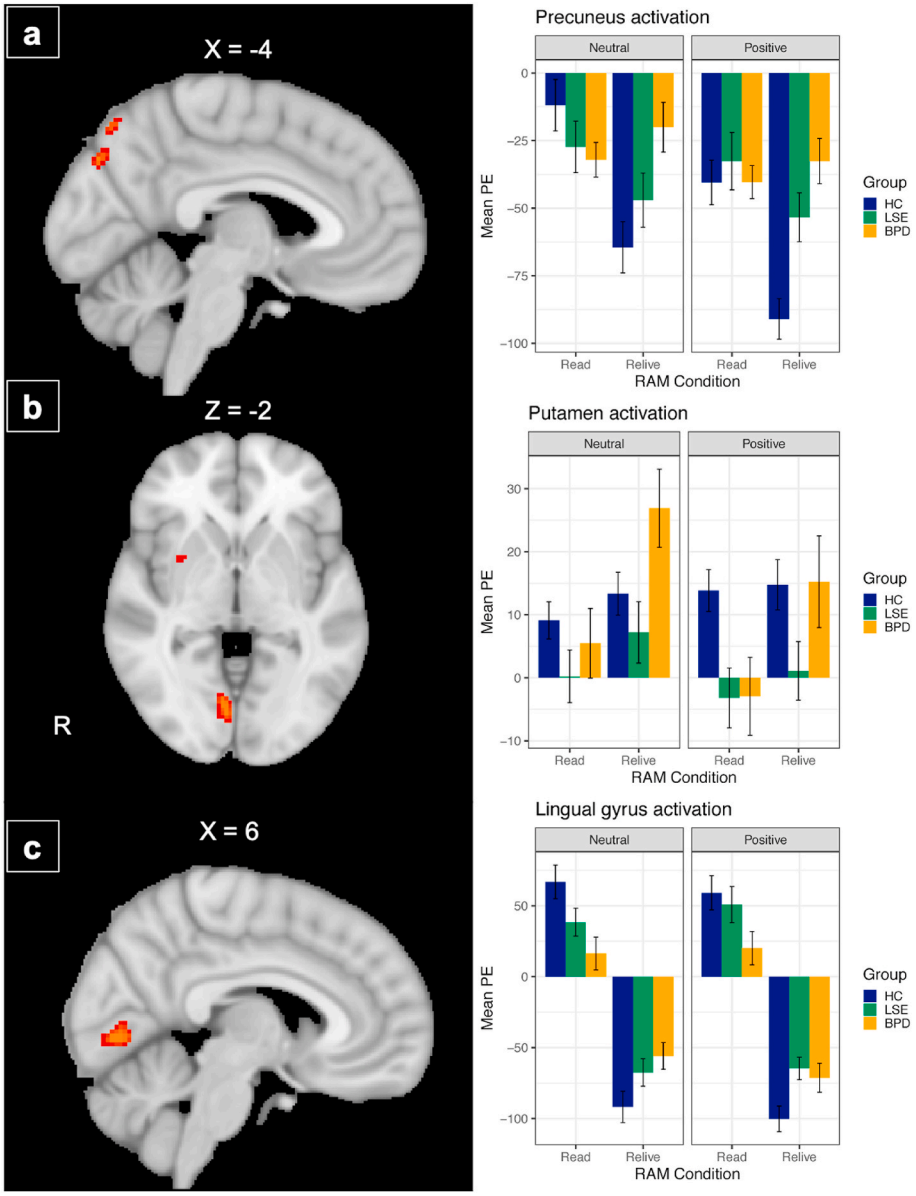


**Fig. 3.** Left panel: Activation differentiating individuals with BPD from HC in a) precuneus, b) putamen and c) lingual gyrus and putamen for reliving compared to reading memory. Results are based on permutation tests with TFCE correction. Right panel: Graphs depict strength of activation as indicated by mean parameter estimates of the precuneus, lingual gyrus and putamen cluster, averaged per group in four different phases of RAM task. Error bars represent standard errors around the mean.

[−176.07, −141.73]) as did LSE ($b = -110.76$, $SE = 9.13$, $t = -12.13$, *98% CI* [−131.84, −89.59]). It should be noted that the direction of effects was the same for individuals with BPD and HC, however, the difference in lingual gyrus activation from reading to reliving memories was larger in HC than individuals with BPD.

Finally, and remarkably, a whole brain one-sample *t*-test per group on the contrast positive compared to neutral reliving revealed no above threshold mean activation difference for either of the groups. Moreover, a whole brain *t*-test indicated that individuals with BPD did not differ from HC or from LSE in activation for positive compared to neutral reliving. A whole brain one-sample *t*-test per group on the contrast neutral compared to positive reliving was associated with increased PCC, precuneus and lingual gyrus activation, see Fig. S2 and Table S8. A whole brain *t*-test indicated that individuals with BPD did not differ from HC or from LSE in activation for neutral compared to positive reliving.

### 3.5. Exploratory analysis of the role of vividness in reliving

In order to better understand the role of vividness in the neural mechanisms of reliving memories, we used regression analyses to explore whether vividness was related to bold responses in the brain areas found to differentiate individuals with BPD from HC in the contrast of reliving vs reading (i.e. areas found in precuneus, lingual gyrus and putamen). These regression analyses indicated that vividness was negatively related to activation in the precuneus and lingual gyrus, while being unrelated to the putamen activation i.e., with lower vividness during reliving being associated with increased precuneus and lingual gyrus activation, see Fig. S3.

### 3.6. Covariates analyses

We checked whether education level, medication status (yes/no) or number of days between appointments influenced the results. When added as covariate to the analyses, education, medication and days between appointments had no influence on the results of mood, state self-esteem or vividness. Adding these confounds to the contrast reliving compared to reading memories did influence the fMRI results. Activation in the putamen became non-significant when adding days between appointments and education level (but not medication). Lingual gyrus activation was least affected by adding confounds, except for medication

status and education level. Precuneus activation became non-significant when adding education level or days between appointments. Education level was related to activation in the superior frontal gyrus during reliving compared to reading memories.

## 4. Discussion

This study sought to investigate whether women with BPD can benefit from reliving positive autobiographical memories in mood and state self-esteem and to understand how memory vividness and underlying neural processes facilitate or obstruct memory reliving. When memory reliving is structured, women with BPD report enhanced mood after reliving positive memories compared to neutral memories. Moreover, reliving positive memories improved state self-esteem in women with BPD. These findings are in line with another study that found that women with BPD can increase positive feelings using positive imagery after negative and neutral mood induction (Jacob et al., 2011). In addition, we found that the vividness of positive memories contributed to a better mood and increased state self-esteem. This suggests that vividly reliving positive memories has the potential to improve mood and state self-esteem in women with BPD. At the same time, the vivid reliving of positive and neutral memories remained challenge for women with BPD, who reported lower vividness. Moreover, women with BPD showed differential activation in the precuneus and lingual gyrus when reliving memories, which was inversely related to memory vividness.

In general, the neural findings indicated that in all three groups reliving compared to reading memories activated areas relevant for the autobiographical memory network including hippocampus, amygdala, and mPFC, indicating that the RAM task, and specifically the reliving condition, induced the re-experiencing of memories (Svoboda, McKinnon, & Levine, 2006). Interestingly, while we found that HC showed a strong deactivation of the precuneus from reading to reliving memories, women with BPD showed a more stable level of activation (i.e., less deactivated). Moreover, less deactivation in the precuneus was associated with lower memory vividness. Although, the precuneus has been associated with higher vividness in episodic memory more generally (Fletcher et al., 1995; Richter, Cooper, Bays, & Simons, 2016), it should be considered here that activation was found for personally relevant memories and was measured within a clinical group. Within autobiographical memory tasks, the precuneus is associated with being able to link self-relevant experiences in time and with shifting perspective on a past self (Hebscher, Ibrahim, & Gilboa, 2020; Iriye & St Jacques, 2020; Northoff et al., 2006; Peer et al., 2015). Specifically, the precuneus activation seems relevant for the emotional experience of the memory (St Jacques et al., 2017). Previous research found that for women with BPD increased precuneus activation was related to better emotion regulation when retrieving upsetting memories (Silvers et al., 2016). However, in the case of positive memories lower vividness and less deactivated precuneus may dampen the positive effect on mood and feelings about the self (Engelhard et al., 2010; Hornsveld et al., 2011; Korrelboom et al., 2011; Philippe et al., 2009). For future studies, it would be interesting to further understand whether woman with BPD experience an alteration in their ability to vividly relive personal memories, or whether particularly memories of positive and neutral valences are experienced in a different way. In case of the latter, it could be speculated that a less deactivated precuneus together with lower vividness may be experienced as a more distant or less self-relevant reliving experience for women with BPD. The manner of reliving could involve linking the relived event to other events (anecdotally participants with BPD often noted that they involved other related memories that were potentially more negative). It could also indicate that they may have more difficulty with immersing in the memories which may contribute to lower self-relevancy of positive experiences. Future clinical research could further study this for example through measuring vividness of mental imagery in general, or through including the degree of first- or third-person perspective taking on a memory-by-memory basis (Chiu, Ng, Kwok, & Tollenaar, 2020).

The role of the lingual gyrus is less clear as it is not commonly found in studies on autobiographical memory (Svoboda et al., 2006). In both HC and women with BPD, the lingual gyrus was more activated during reading than reliving. This may indicate the relevance of the lingual gyrus in visual word processing during the reading condition (Mechelli, Humphreys, K, Olson, & Price, 2000). However, this may not necessarily explain differences between the BPD and HC group, particularly during the reliving. The lingual gyrus has been found to be relevant for holding something in the mind's eye when it is not externally present (Benedek et al., 2016) and may therefore be relevant in switching from the reading (external) to the reliving (internal) phase. Future research is needed to clarify the role of the lingual gyrus in autobiographical memory reliving.

Although, women with BPD showed different bold responses during reliving compared to reading memories, positive compared to neutral memories did not reveal neural differences. Neural differences in reliving may therefore not be related to valence per se but rather to vividness, as indicated by the affective and neural results.

The inclusion of a second control group with equally low feelings of overall self-worth (trait self-esteem) as the BPD group allowed us to further disentangle the effect of low trait self-esteem on positive memory reliving. Moreover, this group reported a similar degree of current axis I mood disorders as the BPD group. Interestingly, the LSE acted as an intermediate group between women with BPD and HC with respect to affective and neural responses. Mood and state self-esteem improved to the same extend in LSE as in women with BPD though women with BPD reported lower levels of mood and state self-esteem overall. Moreover, the LSE and the BPD group did not differ in neural responses to reliving. The results found in women with BPD may be partially due to low self-esteem or depression, which was present in the LSE group as well. Further research should clarify whether this is a matter of degree in psychopathology severity or a qualitative difference related to personality functioning (Sharp, 2020). As differential functioning of autobiographical memory is a characteristic of various disorders, more research is needed to clarify whether specific patterns of alterations exist or whether this is a transdiagnostic feature. The findings from this study may contribute to further delineating autobiographical memory functioning in women with BPD and in which way positive memory reliving may be supportive in the recovery journey. The findings from this study indicate that the vivid experience of positive memories, may be more challenging for women with BPD, which may have consequences for mood and feelings about the self (Libby, 2008; Libby & Eibach, 2002). Given the potential of reliving positive memories, it may be helpful in the clinical setting to carefully and actively encourage exploration and accumulation of (memories of) vivid positive experiences. To optimize benefits in terms of self-image and mood in the long term, future research should investigate 1) whether the vividness of reliving positive memories can be further facilitated by the use of somatosensory input such as sounds or smells and 2) how positive experiences that may be incongruent with the self can be integrated in a supportive way.

We would like to mention a few strengths and limitations of the study. This is one of the first studies investigating positive autobiographical memories in women with BPD that are personally relevant and ecologically valid, and therefore useful to inform clinical memory-based interventions. Another strength is that we included a second control group matched on low self-esteem and depression to take these factors into account. With respect to limitations, we presented participants with their memory cue in line with memory-based intervention and found that the reliving condition differed from the reading condition in terms of autobiographical memory network activation. However, this also introduced a confound in the level of visual stimulation in the reading condition compared to the reliving condition which may be reflected in the deactivation of the occipital lobe in the mean group results. It should be noted that the group comparisons were of interest and that groups were similarly affected by this confound. Furthermore, like many studies

in this field, we only investigated women with BPD and results may therefore not be generalizable to men. Moreover, we used a fixed order of positive memories following neutral memories, to prevent emotion spill-over effects on neutral memories. It seems unlikely that fatigue impacted findings as self-reported focus was better for positive memories (and did not differ between groups). However, additional analyses indicated that memories relived at later trials and that were rated as more pleasant, were relived with higher vividness. In future studies, counterbalancing of valence of memories may help to control for emotional spill-over and learning effects, but this also has disadvantages, as it will diminish the differences between conditions. Moreover, from a clinical perspective, it is interesting that rehearsal and training can increase the vividness of memories and that this already takes place within this short time frame. This further underlines the relevance of positive autobiographical memory retrieval for women with BPD in a clinical setting. Finally, it should be noted that additional sensitivity analyses suggest that in particular the activation in the putamen and to some degree precuneus and lingual gyrus may be affected by confound variables. Replication of these findings are therefore warranted. Even though the neural findings were non-specific to valence and could be an indication of general reliving difficulties in women with BPD, other studies have revealed a different quality of trauma versus neutral memories in terms of neural activation patterns (see e.g. Schmahl et al., 2003). It could be that for people with BPD positive memories are more akin to neutral memories. This study points to the importance of the quality of the memory such as vividness in further elucidating the affective and neural response of reliving positive memories in people with BPD. In future studies, it would be interesting to assess other potential relevant mechanisms such as perspective taking per memory as an indication of memory centrality to the self and investigate how this relates to precuneus activation. Furthermore, when reliving of positive memories is repeated, the experience of positive emotions may be facilitated and these memories may become more central to the self (Korrelboom et al., 2011). For a future study, it would be interesting to investigate whether the mechanisms found in this study, specifically memory vividness and lower precuneus activation, contribute to better outcomes of a memory-based intervention.

To conclude, women with BPD may experience more challenges in reliving both neutral and positive autobiographical memories as indicated by lower vividness and less deactivation in the precuneus. Nevertheless, women with BPD do seem to benefit from reliving positive memories, at least in the short term. With vividness as a target for further improving memory reliving, positive memories may have the potential to regulate emotions and strengthen self-image in the clinical setting in people with BPD.

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## Ethics statement

The study was approved by the medical ethics committee of the Leiden University Medical Center (P12.249) and conducted in accordance with the Helsinki Declaration of 1975, as revised in 2008 and the Dutch Medical Research Involving Human Subjects Act (WMO). All participants signed informed consent.

## Declarations of interest

None.

## Data accessibility

The de-identified data, analysis scripts and materials for this study are made available on DataverseNL and the MRI analysis results are available on Neurovault (https://identifiers.org/neurovault.collection:6020). For any questions or additional material, please contact the corresponding author.

## CRediT authorship contribution statement

**Charlotte C. van Schie:** Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft, All authors contributed to the study design, Writing – review & editing. **Chui-De Chiu:** Funding acquisition, Conceptualization, Methodology, Investigation, Writing – review & editing, All authors contributed to the study design. **Serge A.R.B. Rombouts:** Funding acquisition, Supervision, Writing – review & editing. **Willem J. Heiser:** Funding acquisition, Supervision, Writing – review & editing, All authors contributed to the study design. **Bernet M. Elzinga:** Funding acquisition, Conceptualization, Methodology, Supervision, Writing – review & editing, All authors contributed to the study design, All authors approved the final version of the manuscript for submission.

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## Appendix A. Supplementary data

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