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Overlapping genetic influences between creativity and borderline personality symptoms in a large Dutch sample

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Creativity and mental disorders are sometimes seen as intertwined, but research is still unclear on whether, how much, and why. Here we explore the potential role of shared genetic factors behind creativity and symptoms of borderline personality disorder (BPD, characterized by mood swings and randomness of thoughts). Data were collected from 6745 twins (2378 complete pairs) by the Netherlands Twin Register on BPD scores (PAI-BOR questionnaire) and working in a creative profession (proxy for creativity). First, we tested whether there is an association between BPD symptoms and creative professions. Results confirmed that individuals scoring higher on the BPD spectrum are more likely to have a creative profession (Cohen's d = 0.16). Next, we modeled how much of this association reflects underlying genetic and/or environmental correlations—by using a bivariate classical twin design. We found that creativity and BPD were each influenced by genetic factors (heritability = 0.45 for BPD and 0.67 for creativity) and that these traits are genetically correlated *rG* = 0.17. Environmental influences were not correlated. This is evidence for a common genetic mechanism between borderline personality scores and creativity which may reflect causal effects and shed light on mechanisms.

"*It pays to keep an open mind,*
but not so open your brains fall out".
- Carl Sagan.

There is an ancient, almost proverbial intuition that links creativity with psychiatric vulnerability and mental disorders. Millennia ago, Aristotle already epitomized: "No great genius has ever existed without a strain of madness"[1]. Some famous anecdotes lend weight to this statement. The artist Salvador Dalí had been diagnosed with psychotic illnesses[2], interlinked with both his unusual persona and masterpieces of hallucination-like qualities (like his late painting "La persistencia de la memoria (1931)"). The musician, Odette, was diagnosed with Borderline Personality Disorder giving the lyrics of her personal album a deeper sense. Vincent van Gogh had severe mood swings that could get him "absorbed in the moment […] in a fury of work" or "lying in a deep, dark pit, powerless to do anything"—probably due to bipolar disorder and borderline personality disorder[3].

A connection between creativity and mental disorders has been the subject of theoretical as well as empirical investigations[4]. Empirical studies and meta-analyses show the existence of discrepancies: some confirm a connection (with a variety of proposed causal mechanisms), while others refute this association (for an in-depth look into these discrepancies, see[5–8]). This lack of consensus could be due to methodology issues. Previous studies are generally hampered by small cohorts, lack of standardized tools to assess creativity, or the use of retrospective biographies to establish diagnoses[8,9]. Here, our goal is to: (1) test the association between being in a creative profession and symptoms of borderline personality disorder (BPD); (2) test whether this association shares some of the same genetic predispositions and environmental experiences.

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Creativity

Creativity is defined as the ability to generate ideas or products that are both original and, in some way, useful[10]. It is considered a positive trait that may have helped humans survive and adapt to a changing environment. As with many other complex traits, creativity is considered a continuum that varies among people. Some individuals have hardly any creative capacity and others are highly creative, with most of the population somewhere in between[11].

Borderline personality disorder (BPD)

Borderline personality disorder (BPD) is a severe mood and personality disorder. The lifetime prevalence of a clinical diagnosis in 2018 was estimated to be 5.9 percent in the general population in the USA[12]. In a study based on the Netherlands Mental Health survey, it was found that 25.2% of the population had 1 to 2 symptoms, 3.8% had 3 to 4 symptoms, and 1.1% had 5 or more BPD symptoms[13]. BPD symptoms include symptoms in common with other disorders such as schizophrenia or bipolar disorder—disorders that have previously been associated with creativity, but not always[5–8,14] (more on this later). Individuals diagnosed with BPD may experience intense and highly variable moods as well as distorted and unstable self-image or sense of self. They also tend to view things in extremes. Their interests and values can vary quickly (leading to impulsive behavior) and their feelings for others can change from one extreme to the other (leading to unstable relationships and emotional pain)[15]. Additional symptoms may include feelings of dissociation or feelings of unreality[16], self-harm, suicidal thoughts, and other less common symptoms like acoustic hallucinations[17]. Milder symptoms of BPD are also common in the general population and this supports the concept of a vulnerability model, where an increasing number and severity of symptoms leads to a higher probability of a clinical diagnosis. In other words, BPD is a spectrum.

Association between creativity and BPD

When addressing the association between mental disorders and creativity, initial studies focused on schizophrenia. More recently, a relationship has been found between creativity and bipolar disease and other mood disorders[5–8,14]. Therefore, some results claim creativity and psychopathology to be positively associated, others show no association, and others still show a negative association[8,9]. However, such studies have reached contradictory conclusions—in part due to the complexities of assessing creativity and issues with statistical power[8,9]. Much less is known on the association of creativity with borderline personality disorder (BPD)—there are almost no studies on its potential association with creativity[18], and much remains inconclusive.

But even if we grant that creativity and mental disorders—and specifically BPD—are connected, what can be the cause of that? Given that both mental disorders and creativity have strong genetic influences, perhaps their association could have genetic sources in common.

Genetics of the association

Previous studies found that creativity has a high heritability—in other words, the differences in creativity between people are to a large extent due to genetic variation. In a twin study, Piffer & Hur (2014) estimated the heritability of creative achievement to range from 43 to 63%, depending on the type of assessment[19]. Roeling et al. (2017) measured "being in a creative profession" as an approximation of creativity and found a heritability estimate of 70% in a Dutch twin-sibling study[20].

As far as we know, there are a few inconclusive studies on borderline personality and creativity specifically, and the closest approach is the study about the association between mood disorders and artistic creativity. Research into this area has suggested that subjects with cyclothymia and first-degree relatives of subjects with manic depression had higher creativity scores than controls[21]. Carson et al. (2011) concluded that prominent creative people incurred a greater risk for mood disorders than their less creative counterparts. And compared with the general population, creative people in all professional categories demonstrated higher rates of undifferentiated mood disorder[22]. The authors suggested that mild forms of bipolar pathology or genetic risk for bipolar disorder are more beneficial to creative output than more severe forms of the illness. In a different study, Andreasen also found that both mood disorders and creative interests tended to run in families, concluding that "affective disorder may be both a 'hereditary taint' and a hereditary gift"[7].

Considering the lack of studies on both creativity and BPD, here we describe results from other mental disorders with similar symptoms. For example, for schizophrenia, empirical findings implicate a relationship between creativity and familial risk of schizophrenia in adopted children[23,24]. In a different study, Higier et al. (2014) examined individuals with bipolar disorder and their healthy co-twins and found an increased sharing of positive temperament traits, schizotypy, impulsivity, and sensation seeking. These personality features were correlated with increased verbal learning and fluency in the co-twins. These data provided further evidence to suggest that creativity may result from the combined effects of bipolar spectrum traits and enhanced cognition[25].

Genome-wide association studies (GWAS, where estimates of an association between DNA variants and a phenotype are obtained) have confirmed the genetic association between creativity and schizophrenia[26,27] and also bipolar[26]. Furthermore, Li et al. (2020) revealed that a diagnosis of schizophrenia, depression, and risky behaviors, but not bipolar disorder, was significantly correlated with creativity through shared DNA variants (a DNA variant is a change in the DNA sequence of a gene so that it differs among individuals in a population). Rajagopal et al. (2023) found that having an increased risk for psychiatric disorders, language ability, and creativity might have overlapping genetic roots[28].

By combining multiple GWASs, genetic correlations can be estimated, but with the caveat that accuracy depends on how many of the relevant genetic variants have been found/included. And such analysis cannot assess environmental correlations among two traits (which represent all the life experiences in common that might underlie both traits)[29]. In contrast, research designs based on twin, adoption, and family data can provide

an estimate of non-genetic (environmental) correlations underlying an association between traits, as well as a potentially more complete and accurate estimate of genetic correlations.

Using a genetic epidemiological approach with twins can be an important, and complementary method to elucidate the link between creativity and psychopathology. Because environmental/experiential factors are also critical for mental health and creativity, classical twin studies are a powerful study design[30]. Of note, however, no previous studies tried to estimate such influences between creativity and borderline personality disorder. This is a pity, because BPD is a promising avenue of research on creativity—with many symptoms in common with better studied traits such as schizophrenia and bipolar disorder.

In addition to being a good candidate symptoms-wise, borderline personality disorder also has, like schizophrenia and biopolar, multiple genetic, environmental, and social factors behind it, like family history, genetic vulnerability, and traumatic life events[31]. Distel et al. (2009) showed that genetic factors play a role in BPD, increasing risk among relatives[32]. Lubke et al. (2014) showed a SNP heritability of 23%[33] while Carpenter et al. (2013) concluded that the best evidence to date supports a gene-environment correlation (rGE) model for borderline personality traits, indicating that those with a genetic risk for BPD are also at increased risk for exposure to environments that may trigger BPD[34].

Given the background of previous findings described above, our study here aims to test two main hypotheses in the Netherlands Twin Register: 1) creativity and borderline personality disorder score are associated, so the higher the score for borderline personality, the higher the chances to be in a creative profession; 2) The BPD-creativity association is in part explained by overlapping genetic factors (genetic correlations) and overlapping environments/experiences (environmental correlations).

Materials and methods

Participants

Participants included in this study were part of the Netherlands Twin Register (NTR), a national register with extensive data collection on mental health, personality, lifestyle, demographics, etc. The only inclusion criteria for being part of the NTR is to be a Dutch-literacy twin or a relative of a twin. The representativeness of the general population has been assessed previously[35] with positive results. Our study included data from two surveys completed in 2004–2008 (called here "survey 7"[36]) and 2009–2012 ("survey 8"[37]) as described in[38,39]. The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration. Data collection was approved by the Central Ethics Committee on Research Involving Human Subjects of the University Medical Centers Amsterdam. Informed consent was obtained from all individual participants included in the study. Ethical approval numbers are as follows: ANTR7 (IRB00002991/03-181), ANTR8 (NL25220.029.08/2008-244.

Data were available for 12,939 twins (4610 complete twin pairs). Data from triplets or second twins in the same family were excluded. We removed data from twins with missing zygosity (N = 344). We kept only the individuals who completed surveys that included the PAI-BOR (see below) and questions about their profession, which were coded to reflect if a person worked in a creative profession. There were 4326 families in which one or two twins participated, with 6745 individual twins, with 2378 pairs with data for both twins. These twins were either identical twins (aka, monozygotic twins, MZ, who share nearly all the same DNA) or fraternal twins (aka, dizygotic twins, DZ, who share on average half of their DNA). Of the 6745 individuals, 990 were monozygotic males, 555 dizygotic males, 2569 monozygotic females, 1255 dizygotic females, and 1367 dizygotic opposite-sex. The mean age for the twins was 41.51 [standard deviation (*SD*) 12.41, range 19–90 years].

Zygosity (whether twins are monozygotic or dizygotic) was determined either by genotyping or from self- and parental report answers to survey questions on physical resemblance. DNA and survey zygosity agreement reached more than 96%[39].

Measures

Creative occupation

As described in Roeling et al., individuals were asked to report a detailed description of their profession[20]. Creative professionals were defined as those having positions in the fields of dance, film, music, theater, visual arts, architecture, or writing (coded as yes/no). Individuals not working at the moment of the survey (e.g. retirement, illness, housewives/housemen) were asked for their past occupation to determine their creative profession status. Housewives or housemen who had not worked in any occupation before were coded as non-creative. When full-time or part-time education was reported, creative profession was coded as missing[20].

BPD symptoms score

Scores for borderline personality have been previously analyzed in the NTR[40,41]. The BPD characteristics/symptoms were assessed by the Personality Assessment Inventory-Borderline Features scale (PAI-BOR)[42]. The 24 items of this scale include stability of mood and affects, anger control, self-image, feelings of emptiness, intense and unstable relationships, and self-harm and are rated on a four-point scale (0–3; false, slightly true, mainly true, very true). Previous studies using multigroup confirmatory factor analysis showed that the PAI-BOR is measurement invariant across sex and age[43,44].

Statistical analyses

Descriptive analyses were done in R v.4.1.0. We performed all modeling and testing in Rstudio, notably with the packages "OpenMx" v2.19.8, "psych" v2.1.6, "ggplot2" v3.3.5, "foreign" 0.8–81, "gee" v4.13–20.

To determine the association between creativity and BP symptoms, we performed a logistic regression analysis on creativity by borderline scale, correcting for familial clustering in a Generalized Estimating Equation (GEE) model.

As suggested by the reviewers, post hoc GEE regression analyses were performed to assess the role of possible confounders—sex, age, IQ, educational attainment, and the big 5 of personality—for creativity, borderline, and its association. These GEE models allow to correct for the cluster of families.

To decompose the phenotypic variances and covariance into genetic and environmental components and to estimate genetic and environmental correlations between creativity and BPD, we conducted univariate and bivariate twin models. The identification of genetic and non-genetic parameters in the classical twin models is based on the different degrees of genetic relatedness between monozygotic (MZ) and dizygotic (DZ) twins. MZ twins are (nearly) 100% genetically similar, while DZ twins share ~ 50% of their segregating genes. Because both types of twins are born at the same time and grow up in the same household, MZ and DZ twins share features of their environment and experiences—called the common environment (C), which might affect their trait resemblance. Unique environmental factors and experiences (E) cause differences within MZ and DZ pairs and include all influences associated with "unique" environments (aspects of the environment that differ among siblings), and all forms of error and random noise. E factors are correlated zero by definition in MZ and DZ pairs. When there is a higher resemblance between MZ twins than between DZ twins for a trait, this indicates an influence of genetic factors. Twin resemblance can be a function of additive genetic influences, or an influence from interactions between alleles at the same locus (dominance) or between alleles at different loci (epistasis). We modeled additive genetic influences, based on the earlier analyses of these data[20,26,32].

We estimated first phenotypic correlations between creativity and BPD, and then univariate twin correlations for these two traits, and cross-trait correlations, i.e. BPD in one twin with creativity in the cotwin. Tetrachoric correlations were estimated for the dichotomous traits (creativity). These are based on modeling a continuous liability distribution of the observed creativity variable, for MZ twins and DZ twin pairs[45] (for more detail see explanation of the 'liability' model below). For the continuous borderline scores, Pearson correlations were estimated for MZ and DZ twin pairs[46]. To evaluate the correlation cross-trait between a dichotomous and continuous trait, a point-biserial correlation was estimated, with a total of 4 correlations, within-person in MZ and in DZ twins, cross-trait within-twin in MZ twins, cross-trait cross-twin in DZ twins[47].

Genetic structural equation modelling[48] to estimate genetic and environmental influences was performed in OpenMx[49], first in a univariate classical twin model for each trait separately. For the creativity data, we assumed an underlying 'liability' model[50], in which the variable was assumed to reflect an imprecise measurement of an underlying normal distribution of liability, with zero mean and unit variance. A threshold acts as a reference for the prevalence of the different categories in the population[51]. On the observed scale, creativity was coded as 0 (never worked in a creative profession) and 1 (worked in a creative profession). The estimated threshold divides individuals into a creative and non-creative group and depends on the prevalence in the population[51,52].

The bivariate twin model estimates the correlated influences of additive genetic effects (A), common environmental effects shared by twins from the same family (C), and unique environmental effects (E) on creativity and borderline personality score. These models are based on the comparison of cross-trait cross-twin correlations in MZ and DZ pairs. When these are higher in MZ than in DZ pairs, the correlation between traits is due to correlated genetic effects. For a description of twin model methodology and comparable bivariate twin designs, please see the Supplementary material and publications, e.g.[53–55]. As noted previously in the participants section, we included incomplete pairs, but not participants who had BPD scores but lacked creativity data. Possible sex differences in genetic architecture were assessed in previous NTR studies and showed no differences in heritability for BPD[44] or for creativity[20].

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration. Data collection was approved by the Central Ethics Committee on Research Involving Human Subjects of the University Medical Centers Amsterdam. Informed consent was obtained from all individual participants included in the study. Ethical approval numbers are as follows: ANTR7 (IRB00002991/03-181), ANTR8 (NL25220.029.08/2008-244).

Results

In our sample, 6569 individuals never worked in a creative profession (97.39%), while 176 (2.61%) worked in a creative profession. For the BPD score, the mean of the full sample was 14.88 ($SD = 8.14$). The mean BPD symptoms score of the non-creative group was 14.81 ($SD = 8.12$) while the mean of the creative group was 17.45 ($SD = 8.65$) ($T = -4.0021$, $df = 183.36$, $p < 0.001$). The distributions of this variable are shown in Table 1 and Supplementary Fig. 1 for the full whole sample and for the creative and non-creative groups separately.

We first tested whether borderline personality symptom score and creativity are related. The logistic regression analyses showed a significant association between borderline personality symptoms score and creativity ($z = 4.64$, $\beta = 0.29$, $p < 0.001$; OR = 1.34 (1.18–1.51)).

Phenotypic correlations between twins were calculated within traits and cross-traits. Tetrachoric correlations for the creativity variable were $r = 0.68$ (CI = 0.50–0.80) in MZ twins and $r = 0.34$ (CI = 0.02–0.59) in DZ twins. The correlation for the borderline variable in MZ was estimated at $r = 0.43$ (CI = 0.38–0.47) and in DZ was $r = 0.18$ (CI = 0.12–0.24). The point-biserial cross-trait correlation for creativity in twin 1 vs borderline in twin 2 had an estimate for the MZ correlation of $r = 0.06$ (CI = 0.01–0.11) and for the DZ correlation of $r = -0.02$ (CI = −0.07–0.04). The phenotypic correlation between the traits was $r = 0.13$ (CI = 0.07–0.19).

	Total (N = 6745)	Creative (N = 176)	Non-creative (N = 6569)
Age	41.51 ± 12.41	35.77 ± 10.33	41.73 ± 12.43
BDP	14.88 ± 8.14	17.45 ± 8.65	14.81 ± 8.12
Males	2095 (31.06%)	49 (27.84%)	2046 (31.19%)

Table 1. Details of the description of the twin sample for ss with a creative and non-creative profession. The continuous variables (age, and BPD) are shown as mean ± SD. The dichotomous variable (sex) is shown as number count (%).

Univariate genetic models

The best-fitting model for the borderline variable was an AE model with a heritability estimate for borderline personality score of 0.46. The parameters of the model are specified in Fig. 1A. The details of the likelihood ratio test for every model performed are specified in Table 2.

For creativity, the heritability estimate was 0.68 (CI = 0.52–0.80) and an E parameter of 0.32 (CI = 0.20–0.48). The parameters of the model are specified in Fig. 1B. The details of the likelihood ratio test for all the models performed are specified in Table 3.

1. The negative log-likelihood subtracted for the more general model from the -2LL of the more restricted model. 2. Degrees of freedom (df) of the model. 3. The Akaike information criterion (AIC) is an estimator of prediction error and thereby relative quality of statistical models for a given set of data. 4. X^2 test given in the −2LL test. 5. Difference of degrees of freedom equal to the difference in the number of estimated parameters in

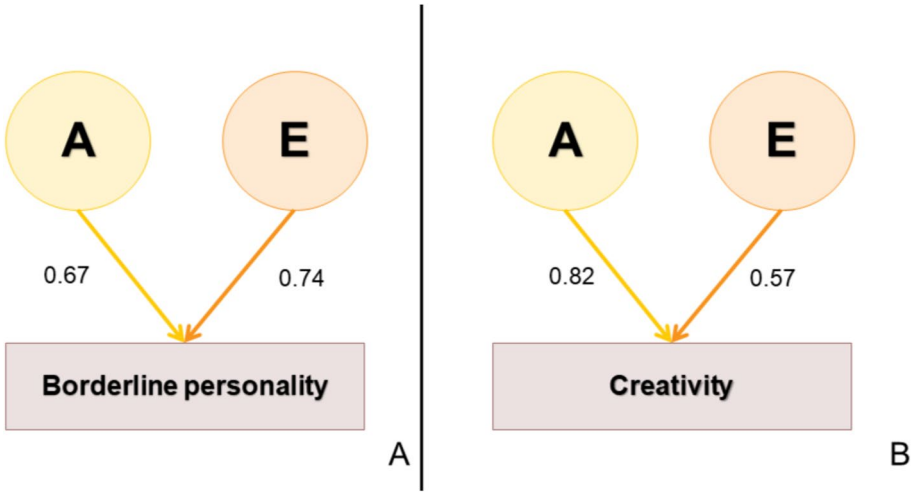

Figure 1. Univariate best-fitting models with parameter specification for borderline (**A**) and for creativity (**B**). The parameters in model A (borderline) and in model B (creativity) are the path values, therefore the sqrt of the standardized variance. A is the additive genetic component and E is the non-shared environment component for each trait.

Fitting model	Compared with	−2LL(1)	df(2)	AIC(3)	$X^{2(4)}$	Δdf(5)	P(6)
ACE	–	47,370.075	6781	47,378.075	NA	NA	NA
AE	**ACE**	**47,372.596**	**6782**	**47,378.596**	**2.52**	**1**	**0.112**
CE	ACE	47,432.325	6782	47,438.325	62.25	1	3.0255e-15
E	ACE	47,694.535	6783	47,698.535	324.46	2	3.5030e-71

Table 2. Details of −2LL tests in the univariate fitting models for borderline personality. 1. The negative log-likelihood subtracted for the more general model from the −2LL of the more restricted model. 2. Degrees of freedom (df) of the model. 3. The Akaike information criterion (AIC) is an estimator of prediction error and thereby relative quality of statistical models for a given set of data. 4. X^2 test given in the −2LL test. 5. Difference of degrees of freedom equal to the difference in the number of estimated parameters in the two models. 6. *P* represents the *p*-value of the test performed. Significant values are in bold. In bold are the models with no difference from the original model, therefore, the best fitting models.

Fitting model	Compared with	−2LL[1]	df[2]	AIC[3]	$X^{2(4)}$	Δdf[5]	*P*[6]
ACE	–	1671.3466	6806	1679.3466	NA	NA	NA
AE	**ACE**	**1671.3467**	**68,077**	**1677.3467**	**1.22e-04**	**1**	**0.991**
CE	ACE	1676.1502	6807	1682.1502	4.80	1	2.840e-02
E	ACE	1720.4348	6808	1724.4348	49.09	2	2.191e-11

Table 3. Details of −2LL tests in the univariate fitting models for creativity. Significant values are in bold.

the two models. 6. *P* represents the *p*-value of the test performed. In bold are the models with no difference from the original model, therefore, the best fitting models.

Bivariate model

The best-fitting model was an AE model with a heritability estimate of 0.45 (CI = 0.41–0.49) for borderline personality symptom score and 0.67 (CI = 0.57–0.80) for creativity. The genetic correlation between borderline personality score and working in a creative profession was estimated at $rG = 0.17$ (CI = 0.01–0.33). This additive genetic effect explained 72% of the phenotypic correlation of 0.13. The non-shared environmental correlation was estimated at $rE = 0.09$ (CI = −0.10–0.27), with the CI indicating this is a non-significant estimate. The specifications of this AE model and the details of the -2LL tests for every model performed are explained in detail in Supplementary Fig. 2, Tables 1 and 2. The representation of the best-fitting model is shown in Fig. 2.

The results of the post hoc analyses for the possible confounders showed that the original genetic correlation between the proxy of the creative profession and the PAI-BOR score of borderline that we found seems to be really about BPD symptoms and creativity. For more detail, see Supplementary analyses.

Discussion

Here we studied the relationship between borderline personality disorder (BPD) and creativity. In a large sample of twins drawn from the general population in the Netherlands, our results confirmed our first hypothesis: borderline personality scores indeed predicted creativity (proxied here as the status of working in a creative profession), with a small effect size. But what could be the sources of this relationship? Are there common genetic predispositions or life experiences that are driving this connection? Our second (and main) hypothesis in this study was that BPD-creativity association is, in part, due to these traits sharing some of the same genetic and environmental/experiential influences. Our models showed that there is indeed a significant genetic overlap between both traits, however (contrary to our expectation) no overlap for the environmental factors. As far as we know, this is the first study to show a genetic influence on the relationship between borderline personality score and creativity.

We think it's worthwhile to first discuss the separate, univariate models. For BPD symptoms, an AE model was confirmed to be the best-fitting model. That means that additive genetic effects (A) and unique environmental

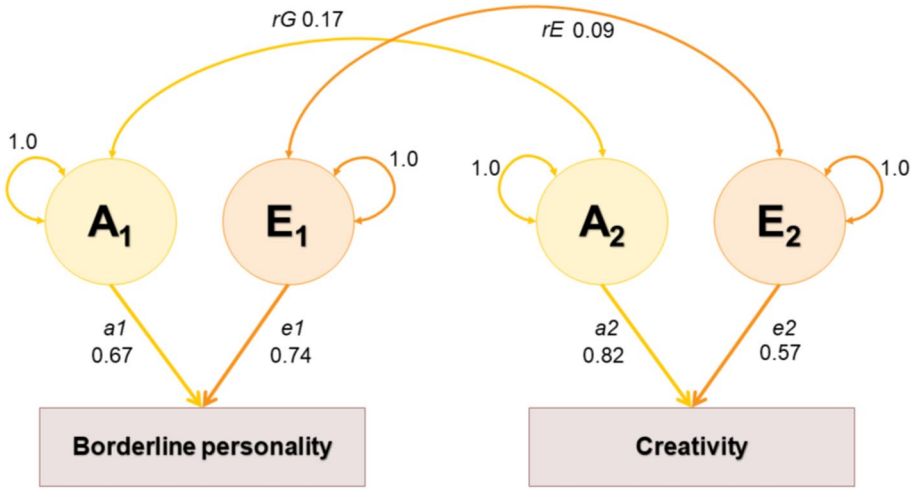

Figure 2. Model specification of the best fitting model (AE). The parameters are shown as path values, therefore the sqrt of the standardized variance. A_1 is the additive genetic component and E_1 is the non-shared environment component for borderline personality; A_2 is the additive genetic component and E_2 is the non-shared environment component for creativity. a1 is the unique genetic contribution for borderline; rG is the genetic correlation between both traits and a2 is the unique genetic contribution for creativity. e1 is the unique non-shared environment contribution for borderline; rE is the non-shared environment correlation between both traits and e2 is the unique non-shared environment contribution for creativity.

effects (E) played a role in the variation of borderline symptoms in our sample, but there are no shared environmental effects (in other words, experiences shared in common between pairs of twins do not make their BPD symptoms more alike). On genetic effects, BPD symptoms showed a heritability of 0.46. These results are in line with previous results published by Distel et al. (2008) in the same cohort, where they also concluded no variance explained by shared environmental factors[44,56]. As for creativity, the best-fitting model resulted in an AE model, without a role of shared environment (C). Working in a creative profession had a high heritability of 0.68. Those results are in line with a previous study in the NTR focused solely on creativity[20].

We note the lack of shared environmental effects (C) that we found for creativity and for BPD (in the univariate as well as the bivariate models). A small C is fairly common in many psychological traits[57,58]. A possible explanation is that interactions of C with additive genetic effects are counted as "A" in the classical twin design[59].

Now onto the bivariate models—the models that have data of both creativity and borderline symptoms together and test the potential overlap in sources of influences. The bivariate model with creativity and borderline personality symptoms showed a small genetic overlap between the traits, but enough to have a significant effect on the model if we remove it. For other, related mental disorders, molecular studies suggest a small overlap with polygenic risk scores for schizophrenia or bipolar disease predicting creativity[26,27] (a polygenic risk score is an index derived from the associations of a GWAS that represents, for each individual, the genetic risk/predisposition for the trait). Note that no past genetic study existed that combines borderline personality and creativity (neither molecular nor familial/twin).

As for environmental effects, we did not find any overlap between borderline symptoms and creativity. The absence of previous studies similar to this approach prevents us from comparing results. The lack of significance in the environmental correlation could mean that "environmental" factors people usually associate with both traits (disorders and creativity)—like for example lifestyle or drug use (selection bias)—are not purely environmental. These factors might (speculatively) be led by their genetic component.

In light of our main results on the shared genetic predispositions between BPD symptoms and creativity: what could be driving such a genetic overlap? There are multiple potential (and non-exclusive) explanations. It could be, for example, that genes which are influencing the creative process are the same that are connected to being prone to mental problems. At the same time, given the genetic correlation and the possible pleiotropism, a molecular approach should be considered in future research to provide additional evidence for the genetic etiology of covariation on borderline personality disorder and creativity. Or it could be because these genes make people more likely to both gravitate towards a creative profession (for non-creative reasons, like personality) and gravitate towards friend groups/profiles that makes them more vulnerable to BPD. Here we favor another explanation inspired by empirical findings from other fields (on the role of mania/obsession and randomness in creativity, described below[60,61]) as well as famous anecdotes (of disturbed creative geniuses). We believe our results show a genetic overlap because there is a potential causal role from mood swings, random thoughts, and hallucinations (all BPD symptoms and genetically influenced) on creativity. How could this causal mechanism work?

For mood swings (mania/depression): Research in Psychology and Psychiatry shows that mood disorder patients who have manic and mixed states have higher creativity than depressive individuals[60]. And a different study found that in healthy, non-clinical subjects, mania risk was related to lifetime creativity and creative personality[61]. (Although not related to performance on a laboratory task of creative insight; which, speculatively, could also mean that our current findings using a measure of creative profession might tie it better with BPD than if we had used creative lab tasks).

For randomness of thoughts and hallucinations: Research in Computer Science suggests that machine learning models and neural networks can perform better and find more solutions to problems if they are given (during training) elements of randomness—which effectively moves the algorithm out of stuck situations/suboptimal solutions[62,63]. Randomness in the algorithm improve the likelihood of locating the global optima or a better local optima[64]. In Psychology, it has been hypothesized that elements of randomness might be the key to human creativity—adding something that no one else could or has added before[65]. This randomness may open the floodgates of the mind and let our imagination run wild. During sleep, for example, randomness is enhanced and helps us solve problems[66]. In an experimental study by Lacaux et al. (2021), they found that participants who slept after seeing a mathematical problem tripled the chance of discovering the hidden rule to solve it compared to participants who remained awake[66]. Similarly (and in a more extreme sense), mental illness could be a factor that would help in the creative process, because sometimes the most bizarre and distant associations (as seen in some mental disorders) can turn into the most brilliant creative ideas in our minds[21].

Given our results of a positive, linear association between BPD and creativity, does that mean that mood swings, random thoughts, and hallucinations are always positively correlated with creativity? Very likely not—at some point, too much mania and randomness will obviously be dysfunctional even to basic day-to-day activities. And remember that in our sample, most participants were healthy, and the average score of BPD was below the clinical threshold. Some authors[22,67] have proposed that creativity relates to psychopathology in an inverted U model. Increasing symptom severity results in increased creativity to a certain point beyond which it starts to diminish—as represented in Fig. 3.

The inverted-U model may be the key to understanding why studies with clinical and non-clinical samples report different conclusions. Studies done with clinical samples frequently conclude that psychopathology and creativity are not related[5,68], or even that these traits are negatively related[69]. But note that, in the inverted-U model, clinical samples are at the extreme end of the distribution and therefore, the expected creativity capacity is low because the harm from too many psychopathology symptoms overcomes the creativity capacity. Results from non-clinical studies are also controversial, but some authors like Csikszentmihalyi[70], Runco[71,72] and Hofmann[9] concluded that slight forms of mental disorders (e.g., mild depressive or hypomanic states) are compatible

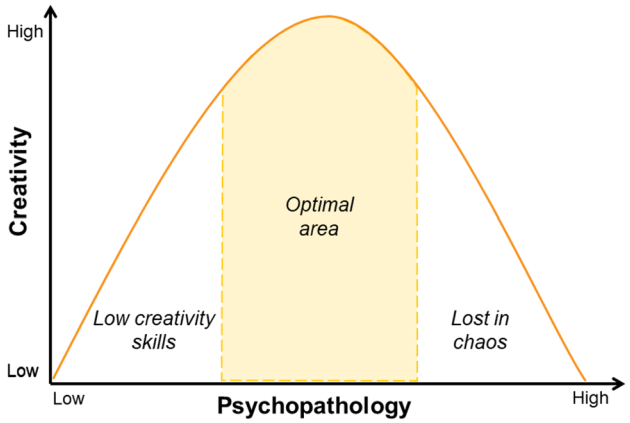

Figure 3. Inverted U model relating psychopathology and creativity. The hypothesis considers people with low psychopathology characteristics would also have low creative capacity. When this psychopathology increases, there is an optimal area where creativity is considerably increased to a certain point beyond which it starts to diminish again.

with creative work, as long as the person has sufficient cognitive capacities, affective energies, and supportive environments.

Under the inverted U model, our study has a special advantage because the BPD questionnaire (PAI-BOR) does not diagnose BPD per se, but scores features related to the BPD syndrome[73]. The mean score for borderline personality in our creative sample was 17.45, meaning that they are not in the extreme to be diagnosed as BPD, and therefore those creative participants could be in the optimal area of creative functioning. Reddy et al. (2018) emphasized that eminent creators may lie on the same spectrum of psychopathological syndromes, but may display a less severe form of it, and hence, use it to their benefit[21]. However, with the present methodology, we cannot directly test if we are indeed seeing an inverted U distribution.

Another feature worth mentioning from our study is the large sample size. The final number of twins used in the twin models was 6745. To our knowledge, that's the largest empirical sample size in any study of creativity and any study of borderline personality (combined and in isolation as well).

In our current study, we cannot conclude if the effects we found are due to something unique about borderline personality or because of comorbidity and/or common features that BPD shares with other disorders. BPD often co-occurs with other mental illnesses, so a person with borderline personality disorder also may be more likely to experience symptoms of major depression, PTSD, bipolar disorder, anxiety disorders, substance abuse, or eating disorders[74,75]. Patients with borderline personality disorder have been shown to have high rates of comorbid disorders: mood disorders 80% to 96%, anxiety disorders 88%, substance abuse disorders 64%, eating disorders 53%, attention deficit hyperactivity disorder (ADHD) 10% to 30%, bipolar disorder 15%, somatoform disorders 10%[76]. Not only that, but BPD is genetically correlated with other disorders as stated by Witt et al. (2017). Significant genetic correlations with BPD were found for bipolar disorder ($rg = 0.28$; s.e. $= 0.094$; $P = 2.99 \times 10 - 3$), major depressive disorder ($rg = 0.57$; s.e. $= 0.18$; $P = 1.04 \times 10 - 3$) and schizophrenia ($rg = 0.34$; s.e. $= 0.082$; $P = 4.37 \times 10 - 5$)[77]. Then, it's likely that analyses on those disorders might show some genetic correlations with creativity as well. Future studies should also look at these comorbidities to further clarify how much the association between creativity and borderline overlaps with (or is partly driven by) other traits. Given past research, we think that some features and comorbidities of borderline would be positively associated with higher creativity- like the mania and mood swings characteristics of bipolar disorder, and the randomness of thought and hallucinations related to schizophrenia. While other features, like eating disorders, PTSD, and anxiety will probably not be.

Our study is limited in using only self-report data on professions (categorized by us as creative or non-creative), and in the low prevalence of creative professions. Possibly, the focus on creative professions provides a flawed reflection of creativity. Sometimes the typical categorization of "creative professions" can overestimate the creativity involved in the work, like, for example, in the case of musicians who don't compose their own songs. And sometimes such categorization can underestimate creativity, like in professions not typically seen as "creative" but that can involve a considerable amount of creative work, such as in the STEM professions. For example, the mathematician John Nash suffered hallucinations from schizophrenia and these possibly inspired his revolutionary theorems in decision-making[78]. The physicist J. Robert Oppenheimer was also initially diagnosed with schizophrenia (called dementia praecox at that time). Or in cases when participants are still creative in their own time (e.g., in hobbies) which is not captured by this study.

Besides, someone deciding to follow a "creative profession" may not always be due to creative inspiration, but because of the lifestyle (socially) connected to such professions. In other words, the causation from borderline personality to creativity may not be direct but indirect: Mood disorders may cause people to gravitate toward particular subcultures and lifestyles (like a bohemian life) that would make them more likely to be artists. Actually, it may be that lifestyle causes both creativity and BPD, and there is no causal connection between borderline personality and creativity. These possibilities should be studied in further studies.

This study brings new insights to society. If it turns out that Borderline symptoms and creativity are causally connected, a creative therapy could help individuals with mild-symptoms of mental disorders, channeling these symptoms in a hurtless way and helping patients to have a more normal life. In addition, these results could give the general public a better understanding of borderline disorder and give it a less negative perception.

In short, this study provides empirical evidence on the relationship between borderline personality and creativity, adding new knowledge about the shared genetic contributions to this relationship. However, our knowledge of the genetic influence and the causation of this relationship is rather limited, and further studies are needed. Nonetheless, the saying that geniuses are mad, as in Dalí's, van Gogh's, and Nash's examples, may perhaps not be so far from reality—at least in moderate doses of madness.

Data availability

Being part of a national prospective cohort study, Netherlands Twin Registerdata cannot be made publicly available for privacy reasons,but they are available for legitimate researchers via the data access procedure (https://ntr-data-request.psy.vu.nl/). The research data collected by the Netherlands Twin Registry (NTR) are pseudonimized, annotated and stored in the NTR Repository. This is a secure database that is only accessible to our data managers. Metadata (i.e. variable names, labels, counts etc.) can be consulted by researchers in the NTR Data Showcase (https://ntr-data-request.psy.vu.nl/data-showcase.html). The Data Showcase allows researchers to create a list of variables and export it for use in a Data Sharing Request (https://ntr-data-request.psy.vu.nl/submitting-a-data-sharing-request.html). Researchers with an approved data sharing request who abide by the rules of the European General Data Protection Regulation will receive temporary access to the NTR data for their own research projects. More information on our data sharing procedures and associated costs can be found https://ntr-data-request.psy.vu.nl/data-sharing-procedures.html. The datasets used and/or analysed during the current study available from the corresponding author on reasonable request. To reproduce this study, the variables "BOR_7", "bor_8", and the creative profession (not included in the data showcase) “creatief7” and “creatief8” should be requested.

Code availability

https://github.com/NataliaAG99/CreativityBorderlineBivariateTwin.

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Author contributions
NAG conceived and designed the work; performed the analysis, interpreted the data; drafted the paper; and substantively revised the paper. GW acquired the data, interpreted the data; and substantively revised the paper. DIB acquired the data, interpreted the data; and substantively revised the paper. BS conceived and designed the work; interpreted the data; and substantively revised the paper. All authors have approved the submitted version and have agreed both to be personally accountable for the author's own contributions and to ensure that questions related to the accuracy or integrity of any part of the work, even ones in which the author was not personally involved, are appropriately investigated, resolved, and the resolution documented in the literature.

Competing interests
The authors declare no competing interests.

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