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REVIEW ARTICLE

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Components of event-related potentials and borderline personality disorder: a meta-analysis

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ABSTRACT

Background: Borderline personality disorder (BPD) is characterized by symptoms associated with difficulties in emotion regulation, altered self-image, impulsivity, and instability in personal relationships. A relationship has been found between BPD symptoms and altered neuropsychological processes. Studies of event-related potentials (ERP) measured with electroencephalogram (EEG) have found neural correlates related to BPD symptoms. Of note is the P300 component, considered a potential mental health biomarker for trauma-associated disorders. However, no meta-analysis has been found to demonstrate this relationship.
Objectives: To evaluate the relationship between the P300 component and BPD symptoms. To evaluate the relationship of other ERP components with BPD symptoms.
Methods: The method and procedure were adjusted to the PRISMA checklist. The search was performed in three databases: WOS, Scopus and PubMed. A Random Effects Model was used to perform the analysis of the studies. In addition, a meta-regression was performed with % women, Gini and GDP. Finally, a descriptive analysis of the main results found between P300, other ERP components (LPP, P100 and ERN/Ne) and BPD symptoms was performed.
Results: From a review of 485 articles, a meta-analysis was performed with six articles that met the inclusion criteria. A moderate, positive relationship was found between the P300 component and BPD symptoms (REM = .489; $p < .001$). It was not possible to perform meta-analyses for other ERP components (LPP, P100 and ERN/Ne) due to the low number of articles found.
Conclusion: The idea that P300 could be considered for use as a biomarker to identify altered neural correlates in BPD is reinforced. In addition, a moderating effect of inequality (Gini) was detected.

Componentes de los potenciales relacionados con eventos y el trastorno límite de la personalidad: un metanálisis

Antecedentes: El trastorno límite de la personalidad (TLP) se caracteriza por sintomatología asociada a dificultades en la regulación emocional, alteraciones de la imagen, impulsividad e inestabilidad en las relaciones personales. Se ha encontrado una relación entre la sintomatología y procesos neuropsicológicos alterados. Los estudios de potenciales relacionados con eventos (ERP) medidos con electroencefalograma (EEG) han hallado correlatos neuronales relacionados con la sintomatología del TLP. Destaca el componente P300, considerado un potencial biomarcador de salud mental para trastornos asociados a trauma. Sin embargo, no se ha encontrado ningún meta-análisis que demuestre esta relación.
Objetivo: Evaluar la relación entre el componente P300 y sintomatología del TLP. Evaluar la relación de otros componentes del ERP con sintomatología TLP.
Método: El método y el procedimiento se ajustaron a la lista de verificación PRISMA. La búsqueda se ejecutó en tres bases de datos: WOS, Scopus y PubMed. Se utilizó un Modelo de Efectos Aleatorios, para efectuar el análisis de los estudios. Además, se realizó una meta-regresión con % mujeres, Gini y PIB. Finalmente, se realiza un análisis descriptivo, de los principales resultados encontrados entre P300, otros componentes de ERP (LPP, P100 y ERN/Ne) y sintomatología TLP.
Resultados: A partir de una revisión de 485 artículos, se realizó un meta-análisis con seis artículos que cumplían los criterios de inclusión. Se encontró una relación moderada y positiva entre el componente P300 y la sintomatología del TLP (REM = .489; $p < .001$). No fue posible realizar meta-análisis para otros componentes de ERP (LPP, P100 y ERN/Ne) debido a la baja cantidad de artículos encontrados.

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HIGHLIGHTS

- The P300 component of event-related potentials could be considered for use as a possible biomarker to identify altered neural correlates in Borderline Personality Disorder.
- There is support for the proposition that an altered P300 would be present in disorders related to exposure to traumatic events.
- P300 could be used to evaluate the therapeutic processes associated with the clinical symptoms of Borderline Personality Disorder.

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Conclusión: Se apoya la idea de que el P300 podría considerarse para ser utilizado como biomarcador para identificar correlatos neuronales alterados en TLP. Además, se detectó un efecto moderador de la desigualdad (Gini).

1. Introduction

The most current version of the Diagnostic and Statistical Manual of Mental Disorders (DSM-5) describes Borderline Personality Disorder (BPD) as a pattern of instability in personal relationships, self-image, affect, and a high degree of impulsivity (American Psychiatric Association, 2013). At least three dimensions have been identified as characterizing BPD symptoms: 1) emotion dysregulation (e.g. impulsivity under stress, maladaptive behaviours, self-injury, suicidal ideation or attempts); 2) identity disturbance (e.g. unstable self-image or sense of self); and 3) interpersonal disturbances (e.g. unstable interpersonal relationships, frantic efforts to avoid abandonment) (Bohus et al., 2021).

Due to its symptoms and the impairment that people with this disorder have, BPD is considered a severe mental disorder (Kjær et al., 2020). This is reflected by its prevalence. Ellison et al. (2018) reviewed studies published between 1989 and 2016, conducted in the United States, Norway, Great Britain, England, and the Netherlands in a community sample report prevalence of BPD at 0.5% to 3.2%. In psychiatric samples, studies published between 1985 and 2017 were reviewed indicating a prevalence of BPD at 2.1% to 6.4% and an overall mean for all studies of 22.4% (Ellison et al., 2018). Another epidemiological study by Samuels (2011) evaluated 5 articles conducted between the years 2001 and 2010, reporting that BPD has a prevalence ranging from 0.7% to 2.7% (Samuels, 2011).

Although BPD symptoms and their prevalence are clear, its etiology is still unknown. A meta-analysis by Ruocco (2005) provides an explanation from a neuropsychological perspective. It indicates that people with BPD present difficulties in executive functions, such as attention, cognitive flexibility, learning, memory, planning, rapid processing and visuospatial skills (Ruocco, 2005). In addition, neuroimaging studies indicate that people with BPD do not fully activate three neural regions involved in cognitive control: (1) dorsal anterior cingulate cortex, (2) inferior frontal gyrus and (3) inferior parietal sulcus, which would be related to BPD symptoms (Ruocco & Carcone, 2016).

However, there is no single area associated with the etiology of BPD. For example, Pérez et al. (2018) propose that there are disconnections and abnormalities in limbic areas and the prefrontal cortex in people with BPD (Pérez et al., 2018). Bertsch and Herpertz (2021), proposed a model linking neurological alterations to BPD symptoms. These alterations include abnormalities in the medial prefrontal cortex, temporoparietal junction and precuneus, which could lead to difficulties in self-reference and mentalizing others' emotions and intentions, as well as the amygdala and midline structures, which have been associated with hypermentalization in BPD patients (Bertsch & Herpertz, 2021).

Likewise, when faced with emotion recognition tasks, it was found that patients with BPD have a lower fronto-limbic activation pattern compared to the control group, which was characterized by a deeper activation in the anterior cingulate cortex, areas associated with attention modulation, executive functions, complex motor control and error detection (Wingenfeld et al., 2009). This is in contrast to the study by Koenigsberg et al. (2009) where patients with BPD, facing an emotion recognition task, present a neural activation different from the control group, mainly facing negative visual emotion stimuli, this because patients with BPD increase the activation of the primary regions of visual processing, the amygdala, fusiform, precuneus and parahippocampal, which indicates that patients with BPD are more hypervigilant, while the control group uses a more reflective and less hypervigilant network (Koenigsberg et al., 2009).

The aforementioned alterations are believed to be caused by multiple neurobiological systems, however, they could be produced by the main factor at the basis of BPD development: exposure to traumatic events occurring mainly during childhood (Amad et al., 2019; Ball & Links, 2009; Crowell et al., 2009; Jaworska-Andryszewska & Rybakowski, 2022; Stepp et al., 2016; Yuan et al., 2023). Therefore, the intersection of BPD with Posttraumatic Stress Disorder (PTSD), is not surprising (APA, 2013; Carvajal, 2002; Owczarek et al., 2023). In fact, there is a high comorbidity between BPD and PTSD which could be as high as 35% (Flasbeck & Brüne, 2021; Friborg et al., 2013; Pagura et al., 2010) and patients with BPD have reported that at least 76.6% present a trauma in childhood and 93.3% present a trauma in adulthood (Fung et al., 2023).

The connection also extends to Complex Posttraumatic Stress Disorder (CPTSD; World Health Organization, 2022). While PTSD, CPTSD, and BPD do not completely share symptoms, there are overlaps. For example, PTSD shares with CPTSD and BPD core symptoms such as reexperiencing, avoidance, and blunting. In addition, CPTSD shares with BPD

symptoms such as sensitivity, worry, guilt, and detachment (Cloitre et al., 2014). However, certain symptoms such as fanaticism, impulsivity, self-injury and emotional instability are considered characteristic of BPD (Cloitre et al., 2014). In this sense, traumatic symptoms are a fundamental element, being able to provoke the referred neurobiological alterations and being a relevant actor in the etiology of PTSD, CPTSD and BPD, however, the mechanisms that are at the basis of the etiology of these disorders are still unknown, so it is necessary to advance in this line of research (Pagura et al., 2010).

Therefore, the focus of the current scientific debate resides in the effort to elucidate the neurobiological bases underlying traumatic symptoms (Baranger et al., 2020; Ruchsow et al., 2006). To address this challenge, neuroimaging research techniques such as electroencephalography (EEG), a non-invasive method that allows the study of brain bioelectrical activity, which is mainly used to gain insight into neural processing, delivering information about brain disorders and cognitive processes (Amin et al., 2015; Carrión et al., 2009; Maiorana et al., 2016), are utilized. In this approach, a procedure known as Event Related Potentials (ERPs) is usually employed, ERPs are transient components in the EEG, which consists of exposing individuals to a sensory stimulus and recording the resulting brain responses, being able to identify cognitive functions (Georgieva et al., 2015; Hasan et al., 2023; Núñez et al., 2004). ERPs are categorized according to their valence; (i.e. whether they are positive or negative), their latency, which refers to the time from stimulus presentation to brain response, and their topography, which describes the distribution of electrical activity in the brain (Luck, 2014; Núñez et al., 2004).

A prominent ERP component in the trauma literature is the P300 or P3 component. In fact, it has been proposed as a potential biomarker of mental health in trauma-associated disorders (Lobo et al., 2015; Wang et al., 2018; Zukerman et al., 2018). P300 is a late positive (P) wave, peaking at around 300 ms (300) (Fabiani et al., 1998; Friedman et al., 2001; Luck, 2014). It presents two distinctions P3a and P3b. P3a occurs at peak amplitudes over frontal areas and is triggered by infrequent changes in stimuli, while P3b appears in the parietal area and shows changes when the stimulus is relevant to the task performed (Polich, 2012). In addition, the late appearance of the P300 allows evaluating cognitive processes associated with attention and working memory (Duncan-Johnson & Donchin, 1982; Luck, 2014; Polich, 2007) This is relevant to evaluate in BPD due to the alterations at the neuropsychological level described above, similar to what occurs in PTSD where the P300 an has been used to identify attentional bias to stimuli that are relevant to the trauma (Stanford et al., 2001). Due to the relationship between potentially traumatic events and BPD, it is necessary to assess whether the P300 is also related to BPD symptoms.

A review conducted by Flasbeck et al. (2020) to identify altered neural processing in individuals with BPD, reports the existence of a relationship between the P300 component and deficits in inhibitory control, and a relationship between P3a distinction and early evaluative cognitive processing. However, the relationship of other ERP components that could be associated with BPD symptoms has also been reported, as is the case of the relationship with the amplitude of the FRN (feedback related negativity) component and decision making in individuals with BPD where it is possible to observe altered processing (Flasbeck et al., 2020).

In summary, the literature has evidenced a correlation between components of event-related potentials and symptoms of Borderline Personality Disorder. It highlights, P300 as a potential biomarker of psychological trauma, possibly linked to BPD. However, we say 'possibly' because the mainstream scientific literature has not yet provided a meta-analysis that jointly examines this relationship. Also, it remains uncertain whether other components of the ERP would maintain a similar connection to BPD symptoms. To clarify these unknowns, a meta-analysis of previous studies establishing the relationship between ERP components and BPD symptoms becomes imperative. The present meta-analysis resolves these controversies, and its aims are twofold. The first aim is to evaluate the relationship between the P300 component and BPD symptoms; and the second aim is to evaluate the relationship of other ERP components with BPD symptoms. Based on both objectives, two hypotheses are proposed. The first is that the P300 component shows a relationship with BPD symptoms whose effect is like that of relationship with PTSD. Second, there are other ERP components (e.g. FRN) related to BPD in a manner like P300. These hypotheses are based on the relationship of BPD to traumatic events, its high comorbidity with PTSD, and the relationship of these events to P300. The present meta-analysis contributes to the understanding of BPD as a disruptive response related to exposure to traumatic events. Therefore, we also assess whether the social factors of the populations in the studies linked to such exposure (e.g. gender, economic inequality (Gini) and economic growth (GDP); Brewin et al., 2000; Trickey et al., 2012; Xue et al., 2015) are moderators for the relationship between ERP and BPD symptoms.

2. Method

2.1. Search strategy

Reporting methods and procedures were in accordance with the PRISMA checklist (Preferred Reporting

Items for Systematic Reviews and Meta-Analyses). English-language articles published in peer-reviewed journals (indexes) up to June 2023 were processed for inclusion. The search was performed in three scientific literature databases: Web of Science, Scopus, and PubMed. The search terms entered in the bibliographic databases included the following combinations: TITLE-ABS-KEY BPD, ERP and EEG according to the following logical search algorithm: 'borderline' & ('personality' & 'disorder') OR 'BPD' & ('EEG' OR 'electroencephalogram' OR 'ERP' OR 'event related potential' OR 'P300' OR 'P3'). Due to the quantitative focus of this study, we excluded documents such as book chapters, theoretical reviews, systematic reviews, editorial comments, letters or notes, case studies, and other articles that provided non-quantitative information on BPD and EEG. This study was not pre-registered.

2.2. Inclusion and eligibility criteria

The following inclusion criteria were applied to these articles: (1) being written in English or translatable into English; (2) present an empirical and quantitative study; (3) address the relationship of BPD symptoms (based on the DSM-5 criteria) and ERP responses; (4) This variable should theoretically be associated with BPD as a cause and not as a consequence; and (5) have data to perform meta-analytic calculations (e.g. Pearson's correlation coefficient).

2.3. Quality assessment

The assessment of methodological rigour and the possible presence of bias in each of the studies used in the meta-analysis was determined using the National Institute of Health (NIH) version 'Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies' (NIH, 2023). This tool comprises 14 areas of analysis, which considers: formulation of the research question, composition of the study population, recruitment procedures, study power, methods of measuring exposures and outcomes, dropout rate, and statistical approaches used.

Each original evaluation question is classified as 'yes,' 'no,' 'cannot be determined,' 'not applicable,' or 'not reported.' In the present study, a scoring system has been adopted that assigns a score of 1 to 'yes' answers, 0.5 to partial statements, and 0 to 'no' or unclear answers. This scoring system has been recommended by similar research (Gaythorpe et al., 2021) and is intended to quantify the results in a consistent manner.

The description of each criterion is detailed in Supplementary Table S1. As a criterion for the final classification, studies that scored 7 or more points were categorized as high quality (good), while those that scored between 5 and 6 points were considered acceptable (fair). On the other hand, studies that scored less than 5 points were classified as poor quality.

The quality assessment process was conducted independently by two independent investigators (F.S., M.N.), and the results were thoroughly discussed. Disagreements that arose were resolved through constructive discussion.

2.4. Data extraction

The initial search was performed by one of the authors (F.S.), to identify the articles according to the search terms. This was followed by manual inspection to select those that met the selection criteria. Screening was performed by two of the authors (M.L., M.N.) independently, reviewing titles, abstracts, or the full article if relevant. Differences in interpretation were resolved by discussion with a third reviewer (G.S.) to develop a final coding. According to the inclusion criteria, the selected articles were read in their entirety. To classify them, a colour code was used: included in green, excluded in red, doubts in yellow and orange not found, according to Cochrane recommendations (Higgins, 2012).

2.5. Analysis plan

The effect size was determined using Pearson's r correlation between BPD symptoms and the ERP component. Being a standardization of the covariances, Pearson's r has a common metric to assess the size of the effect (Botella & Sánchez, 2015). The selected analysis model is random effects, since it allows for flexible analysis of studies and generalization (Botella & Sánchez, 2015). To analyze homogeneity, the Cochran Q statistic was used, which allows us to identify whether the correlations of the studies estimate the same parametric effect ($p > .05$) (Botella & Sánchez, 2015). In addition, the I^2 statistic was used to assess the differences present between the studies according to the groups of people that comprise it (e.g. age, gender). Multiplying this statistic by 100, the percentage of heterogeneity of the studies is obtained (Botella & Sánchez, 2015).

To rule out publication bias, Rosenthal's N tests (N Rosenthal $>5^*k + 10$), Egger's Z ($p > .05$). The absence of bias is confirmed by graphically locating the scores within the triangle centred on the mean using the funnel plot. In case of being outside the limits, it was analyzed if the residues were within the expected ranges (-1.96 and 1.96; Botella & Sánchez, 2015). Once homogeneity and absence of bias were verified, the effect size and confidence interval of each study and the meta-analysis were plotted using a forest plot. Finally, a meta-regression was performed (Mod; $p < .05$; $R^2 > .5$) based on a mixed effects model and maximum likelihood method aiming to examine the effect of

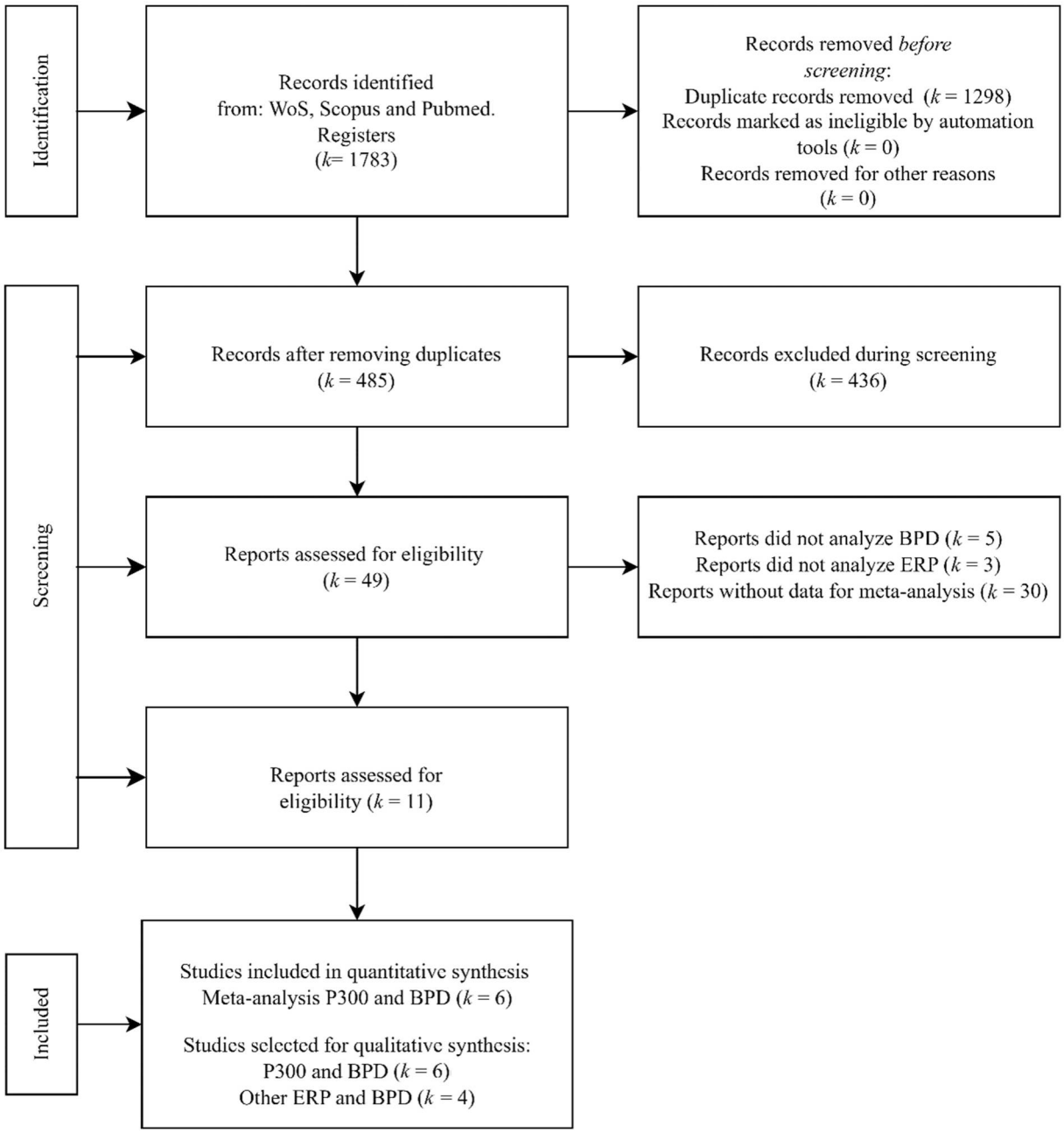

Figure 1. Flow diagram for the study selection process.

variables that theoretically may be influencing the relationship between ERP and BPD symptoms. Indicators of exposed groups such as the female ratio (percentage of women in the sample), inequality index (Gini of the country) and gross domestic product (GDP of the country) were chosen as it has been shown that socioeconomic status and inequality are frequently linked to mental health issues (Harnett et al., 2023; O'Donoghue et al., 2023; Winsper et al., 2020), and mixed results have been reported on the gender-based prevalence of BPD across populations (Arranz et al., 2021; Qian et al., 2022; Sansone & Sansone, 2011). Thus, we hypothesize that these variables could potentially moderate the link between ERP and BPD symptoms. The analyses were performed with R version 4.3.0 using the metafor package.

3. Results

3.1. Selection of studies

We found 1,783 articles that met the initial search criteria. Of these, 644 articles passed the duplication process, and 49 articles passed the exclusion criteria. From these articles, a database was created that could contain at least one study per article reviewed. Of the 49 articles, five did not analyze BPD, three did not analyze ERP, and 30 articles did not present sufficient data for meta-analysis. Four articles were analyzed descriptively, being single studies of a single ERP component (LPP, P100 and ERN/Ne). That is, they do not meet the required minimum. Therefore, it was possible to meta-analyze six articles on the P300 component. In addition, some of these articles presented

Table 1. Summary of studies relating P300 and BPD symptoms.

Author	*n* BPD	Age (M; SD)	% Female	Gini	GDP	Variable	*r*	IC (95%) Lower	Upper
Endrass et al. (2016)	18	30.9; 7.2	72%	.317	4700000000000	Risky decisions (impulsivity) loss condition.	.56	[0,126,	.814]
						Risk decisions (impulsivity) gain condition.	.58	[0,155,	.824]
Xi et al. (2021)	27	24.6; 1.04	37%	.382	17960000000000	Adaptive coping Pz electrode.	.42	[0.048,	.690]
						Impulsivity electrode Cz change condition.	.51	[0.161,	.746]
Ramos-Loyo et al. (2021)	11	24.7; 4.81	100%	.454	1410000000000	Symptomatology BPD electrode Cz neutral condition.	.61	[0.016,	.886]
						Symptomatology BPD electrode Cz pleasant condition.	.85	[0.510,	.960]
						Symptomatology BPD electrode Cz unpleasant condition.	.73	[0.232,	.925]
Stewart et al. (2019)	33	17.2; 1.76	100%	.397	25460000000000	Impulsivity.	.42	[0.090,	.667]
Izurieta et al. (2016)	33	26.7; 6.0	100%	.317	4700000000000	Anger suppression.	.40	[0.066,	.654]
Weinbrecht et al. (2018)	29	27.8; 5.0	86%	.317	4700000000000	Social processing inclusion.	.28	[−0.096,	.586]

Note: *nBPD* = BPD sample; Age (M; SD) = mean and standard deviation of the age of the sample; % Female = % of female in the BPD sample; GINI = Inequality Index; GD*P* = Gross Domestic Product; *r* = correlation coefficient.

Table 2. Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies.

ID	Authors	Criteria Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Score	Quality rating
1	Endrass et al. (2016)	1	1	1	.5	0	0	0	0	1	0	1	0	0	1	6.5	Fair
2	Izurieta et al. (2016)	1	1	1	0	0	0	0	0	1	0	1	0	0	1	6	Fair
3	Ramos-Loyo et al. (2021)	1	1	1	1	0	0	0	0	1	0	1	0	0	1	7	Good
4	Stewart et al. (2019)	1	1	1	.5	0	0	0	0	1	0	1	0	0	1	6.5	Fair
5	Weinbrecht et al. (2018)	1	1	1	.5	0	0	0	0	1	0	1	0	0	1	6.5	Fair
6	Xi et al. (2021)	1	1	1	.5	0	0	0	0	1	0	1	0	0	1	6.5	Fair

Note: Ratings were conducted in accordance with the NIH quality assessment tool.

more than one relationship, so the meta-analysis was performed for a total of 10 relationships between P300 and BPD symptoms. Figure 1 presents the flow chart of the study selection process.

3.2. Sample characteristics

Six articles were included with a total sample size of 151 (M_{age} = 25.75; SD_{age} = 3.91; Female = 82.78%). Only the BPD group was considered in this sample because we sought to analyze the relationship between individuals with BPD symptoms and the P300 component. The studies were conducted in four countries (Germany, China, Mexico, USA). Table 1 presents the characteristics of the studies.

3.3. Assessment of quality

The methodological quality within the included studies varied. Table 1 provides an overview of the 14 quality assessment areas and the overall quality rating indicating risk of bias. Using the guidance provided by the NIH (2023) tool, (1) studies were rated 'good' quality rating, indicating low risk of bias, and (5) studies were rated 'fair' quality rating, indicating some risk of bias.

The main shortcoming in the quality of the included studies is due to the type of 'cross-sectional' study design, which for questions '5, 6, 7,8, 10, 12 & 13' obtained the minimum score since they evaluate characteristics of longitudinal studies. The results of the quality assessment are summarized in Table 2.

3.4. Meta-analysis of the relationship between BPD symptoms and P300

For the meta-analysis, the six selected articles were used, with a total of 10 correlations between P300 and BPD symptoms (k = 10). Overall, a medium and significant effect size was observed (REM = .489; p = .000). The results of the meta-analysis are presented in Table 3 and the forest plot is presented in Figure 2.

The studies showed low heterogeneity (I^2 = .01%; Q = 8.422; p = .492) and an absence of publication bias,

Table 3. Meta-analysis results

		REM														
						IC (95%)		IP (95%)		Heterogeneity tests			Publication bias			
k	*n*	r_z	*r*	SE	*p*	Lower	Upper	Lower	Upper	Q	*p*	I^2	FsN	(5**k* + 10)	Z_{Egger}	*p*
10	151	.534	.489	.073	.000	.373	.590	.373	.590	8.422	.492	.010	210	60	2.503	.012

Note: *k* = number of included studies; *n* = sample; rz = z-valued estimator; *r* = correlation coefficient estimator; SE = standard error; *p* = level of significandce; IC = confidence intervals; PI = pdrediction interval; *Q* = Cochran's *Q*; I^2 = heterogeneity index; FsN = Fail – safe *N* of Rosenthal; Z_{Egger} = Egger test.

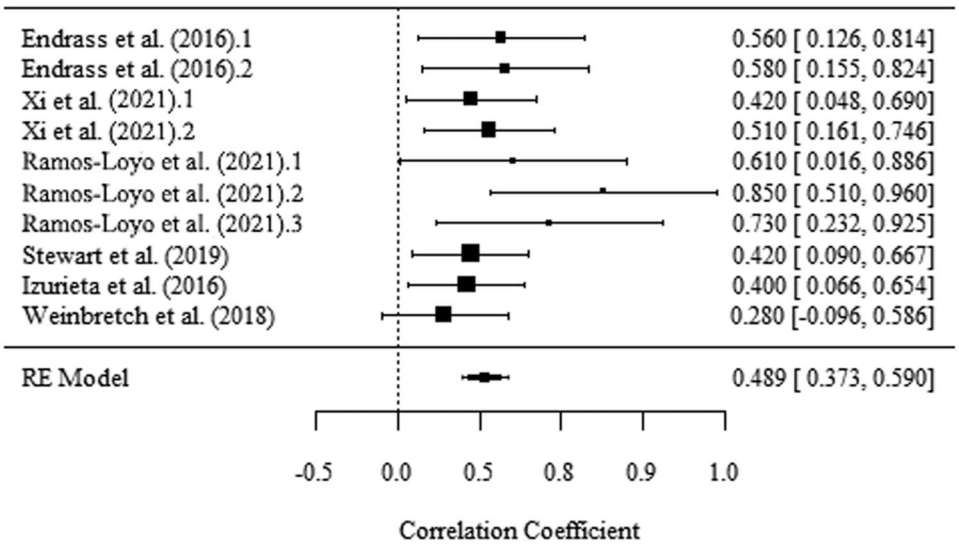

Figure 2. Forest plot for the P300 event-related potential and borderline personality disorder symptoms meta-analysis.

as indicated by Rosenthal's N (Rosenthal's $N > 5^{*}k + 10$; $210 > 60$). However, Egger's Z value was significant, which would indicate the presence of asymmetry in the distribution of effects. Further details of the distribution of effects are shown in Figure 3.

3.5. Influential diagnosticrs

A sensitivity analysis was performed through plots of influential diagnostics to see if any outliers were reported. It was found that no study presented an outlier. The results can be seen in Supplementary Figure 1.

3.6. Meta-regression

To analyze possible sources of heterogeneity, a meta-regression analysis based on a mixed effect model (*MEM*) was performed. The effect of three potential moderators was explored based on the descriptives provided by the studies: percentages of women, Gini and GDP. Only the Gini moderator showed a statistically significant effect. The results are shown in Table 4 and Figure 4.

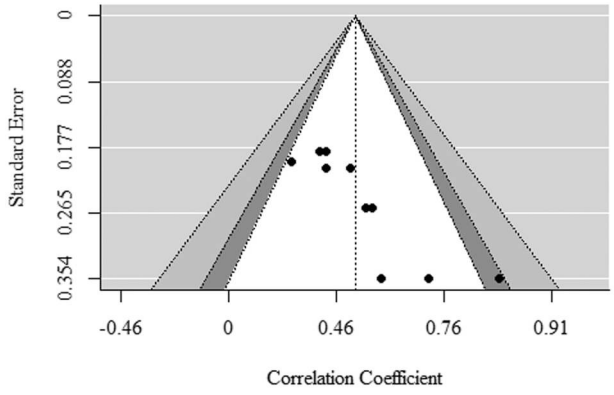

Figure 3. Funnel plot for the P300 event-related potential and borderline personality disorder symptoms meta-analysis.

3.7. Descriptive results

3.7.1. Relationship between P300 and BPD symptoms

Six articles reported at least one relationship between the P300 component and BPD-associated symptoms. For example, in order to evaluate the P300 component and its relationship with reduced risk assessment in BPD patients, Endrass et al. (2016) implemented a Two-choice task to assess impulsivity symptoms, where participants had to choose options, low risk with small potential gains and losses or high risk with larger potential gains and losses. To evoke the ERP response, they used visual stimuli where a green smiling face was associated when the participant selected the gain option and a red frowning face when the participant selected the loss option. A main effect of participants with BPD versus the control group was reported for the high-risk option, indicating that participants with BPD tended to mostly choose the high-risk option. When performing correlation analysis between P300 and risk decisions, positive and significant correlations were found between loss condition ($r = .56$; $p = .03$) and gain condition ($r = .58$; $p = .01$).

Similar results were reported in Stewart et al. (2019) where they sought to study impulsivity symptoms though reward processing, identifying that the feedback process and altered learning are related to BPD symptoms. Through a Guessing Task, participants had to choose a door in which one contained gains and the other losses, then they were told whether the answer was correct (green up arrow) or incorrect (red down arrow). Differences in neural response were reported for both wins and losses, however, correlation analyses indicated that there is a significantly lower P300 amplitude for wins versus losses which was related to worse BPD symptoms ($r = .42$; $p = .015$).

Table 4. Meta-regression results.

			MEM											
						IC (95%)		Heterogeneity tests			Publication bias			
k	*n*	Mod	Estimate	SE	p_{Mod}	Lower	Upper	*Q*	*p*	I^2	FsN	(5**k* + 10)	Z_{Egger}	*p*
10	151	Sex (female)	-.095	.303	.753	-.668	.498	3.149	.790	.000	210	60	1.890	.059
		Gini	3.419	1.616	.344	.251	6.587							
		GDP	.000	.000	.126	.000	.000							

Note: *k* = number of included studies; *n* = sample; Mod = moderator; Estimate = moderator estimate; SE = standard error; p_{Mod}: level of significance moderator; IC = confidence intervals; *Q* = Cochran's *Q*; I^2 = heterogeneity index; FsN = Fail − safe N; Z_{Egger} = Egger test.

Following this line, a relationship between impaired inhibitory control and global BPD symptoms has also been reported by Ramos-Loyo et al. (2021), which the authors characterize based on the DIB-R assessing symptoms such as social adaptation, impulsivity, affective instability, psychosis and problems in interpersonal relationships. The authors studied inhibitory control through emotional stimuli. For this purpose, they used a Go/NoGo task, where participants were shown affective images with pleasant, unpleasant and a neutral stimulus. The stimulus consisted of a vertical bar to the left or to the right and an arrow appearing in the centre of the screen pointing to the left or to the right. The Go condition occurred when the participant points in the same direction as the bar shown to the left or right of the image and they also matched in colour. The NoGo condition was when the participant should refrain from responding. The correlation analysis indicated a relationship between the amplitude of the P3 NoGo and BPD symptoms, these correlations being positive and significant in the three conditions evaluated: Neutral ($r = .61$; $p = .04$), Pleasant ($r = .85$, $p = .001$), Unpleasant ($r = .73$; $p = .01$). The authors point out that the presence of higher amplitudes of P3 in the NoGo task would alter the context-independent inhibition processes and increase the psychopathological symptoms of BPD in emotional contexts.

These alterations at the emotional level have also been reported in difficulties in front of emotion processing, which is linked to affective instability in BPD. Izurieta et al. (2016) studied the time course of facial emotion processing in patients with BPD. They confirmed the presence of biases in facial processing, both in early and later stages. When performing the correlation between P300 and anger suppression in participants with BPD, a significant positive correlation was observed ($r = .40$; $p < .024$) (Izurieta et al., 2016). These results would indicate that there is a higher probability of misclassifying an angry face when it is predominantly happy (Izurieta et al., 2016).

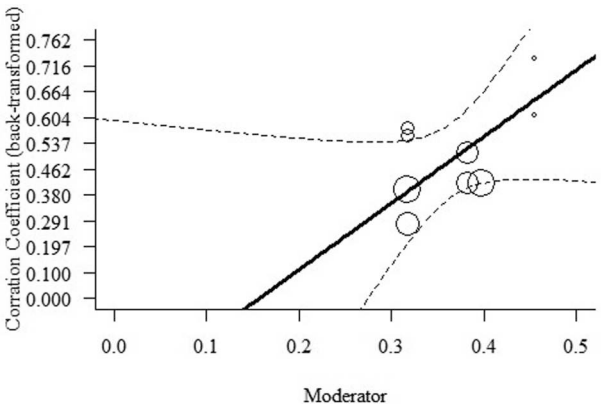

Figure 4. Bubble plot for the P300 event-related potential and borderline personality disorder symptoms meta-regression with Gini as a moderator.

The study conducted by Weinbrecht et al. (2018) evaluated the processing of social engagement in BPD, based on the relationship between difficulties in interpersonal relationships and social exclusion, which are frequent in patients with BPD because of their impulsive behaviour (Weinbrecht et al., 2018). Through a Cyberball paradigm participants performed a task in front of a computer where they threw a ball thinking they were throwing it to other online players. Correlation analysis showed that the relationship between P3 amplitude was positive and significant only in the inclusion condition ($r = .28$; $p = .03$), which would indicate the existence of a bias in social processing of social inclusion, because this condition was present even when participants with BPD were included in a larger amount (Weinbrecht et al., 2018).

Finally, as previously reviewed, individuals with BPD present several difficulties in their executive functions (Ruocco, 2005). Thus, Xi et al. (2021) studied possible alterations in the processing of set changes through a Task Switching paradigm. They found no differences in set processing between the BPD group and the control group. However, it was evidenced that both ERP component P2 and P3 were related to clinical symptoms of BPD. It was identified that P3 amplitude at the Pz electrode correlated positively and significantly with adaptive coping strategies in BPD on the repetition task ($r = .42$; $p < .05$), occurring the same, but in front of the change task and P3 amplitude at the Cz electrode and impulsivity ($r = .51$; $p < .05$) (Xi et al., 2021). The authors indicate that the relationships found would reflect abnormal brain activity in the set-shifting function mainly in the prefrontal cortex and that these results worsen performance when the task involves attentional allocation (Xi et al., 2021).

3.7.2. Relationship between other ERP components and BPD symptoms

Studies were found that reported relationships between ERP components such as LPP, P100 and ERN/Ne and BPD symptoms. The main results found are reported below.

The existence of self-referential processing biases is reported, where individuals with BPD tend to attribute negative content toward the self (Auerbach et al., 2016). Thus, Auerbach et al. (2016) assessed self-referential biases in youth with BPD based on identity disturbance traits. For this purpose, they used a Self-Referential Encoding Task with positive words and negative words. The results of the task were correlated with the positive LPP component. The LPP component appears in front of attentional processes mainly to stimuli with emotional content (Dennis & Hajcak, 2009). The results of the correlations presented a negative and significant relationship in the endorsed positive word condition between early LPP and BPD symptoms ($r = -.42$; $p < .05$), which would indicate the existence of a discrete neural process, which would be contributing to self-referential processing biases in individuals with BPD (Auerbach et al., 2016). The relationship between P1, P2 and late LPP components and BPD symptoms was also assessed, but no significant relationship was presented.

Another study that related LPP to BPD is that of Flasbeck et al. (2017). The study aimed to examine difficulties in interpersonal relationships by assessing empathic differences between the BPD group and the control group. A paradigm was used where participants had to complete a Social Interaction Empathy Task. To do so, participants had to distinguish images depicting physically or psychologically painful interactions and distinguish between physical or psychological pain in social interactions. Correlation analyses showed a relationship between the LPP component and CTQ (Childhood Trauma Questionnaire) scores in the physical pain condition ($r = .47$, $p = .10$) and psychological pain ($r = .54$, $p = .003$). The authors conclude that this relationship would be indicative that individuals with BPD process and evaluate differently at a higher order cognitive level compared to the control group. By presenting a relationship between CTQ and LPP scores in individuals with BPD it is established that trauma would be relevant to BPD (Flasbeck et al., 2017).

As previously reported, individuals with BPD had impaired emotion processing in facial emotion recognition (Izurieta et al., 2016). However, these alterations also transcend to other areas of emotional processing. This happens in the case for affective instability and emotional awareness, where Izurieta et al. (2016), reported a relationship between higher P100 amplitude and decreased emotional awareness in BPD patients in the very angry faces condition ($r = .33$; $p < .07$). The authors propose that the P100 is a component that can be observed in occipital areas and appears at around 100 ms after a visual stimulus. Therefore, the proposed relationship would be indicative of a more negative perception of others due to a hyper-reactivity to information considered threatening (Izurieta et al., 2016).

Finally, Ruchsow et al. (2006) conducted a study where one of their aims was to determine whether impulsivity in BPD patients had an impact on the amplitudes of the ERN/Ne component. The ERN/Ne is an ERP component that relates to errors made in front of a task and appears in the moment right after responding erroneously (Luck, 2014; Ruchsow et al., 2006). Thus, Ruchsow et al. (2006) using a Go/NoGo task and an Eriksen flanking paradigm presented a string of letters in a congruent and incongruent condition. When correlating impulsivity and ERN/Ne amplitudes in BPD patients, three positive and significant correlations are observed for different electrodes, but only in the non-planning impulsivity subtrait: Cz ($r = .66$; $p = .020$), C1 ($r = .69$; $p = .013$) and C2 ($r = .68$; $p = .014$).

4. Discussion

The aim of the present study was to analyze the relationship between P300 event-related potential, other ERP components and BPD symptoms. From the literature review and the use of meta-analysis, it was possible to determine an effect with a moderate and positive relationship between the P300 component and BPD symptoms ($REM = .489$; $p = .00$).

It was possible to observe an altered P300 in relation to BPD symptoms such as risky decision making associated with higher levels of impulsivity, anger suppression characterized by biases to negative emotions, altered social processing in inclusion and difficulties in adaptive coping (Endrass et al., 2016; Izurieta et al., 2016; Ramos-Loyo et al., 2021; Stewart et al., 2019; Weinbrecht et al., 2018; Xi et al., 2021). These symptoms were also accompanied by alterations in cognitive processes which would explain these traits (Di Bartolomeo et al., 2022; Schuermann et al., 2011).

Relationships were also observed in studies with other ERP components (LPP, P100 and ERN/Ne) and BPD symptoms; however, it was not possible to perform a meta-analysis due to the low number of articles found. Descriptively, it is observed that other ERP components could be associated with global BPD symptoms, altered emotional awareness and impulsivity.

Systematic reviews complementary to this meta-analysis reinforce the effects found. Flasbeck et al. (2020) concluded that studies with ERP in individuals with BPD show difficulties in cognitive processing, impaired response inhibition and impulsivity.

However, they state that it was not possible to identify whether these associations are characteristic of BPD symptoms or would be characteristic of the altered cognitive processes (Flasbeck et al., 2020). This could occur because there are no longitudinal studies to determine a cause–effect relationship, and it is unknown whether the characteristics of the altered cognitive processing would be prior to the disorder or if they correspond to a progression at the neurobiological level because of the development of BPD (Winsper et al., 2016).

For their part, the review by Penengo et al. (2022) point out alterations in the amplitudes and latencies of the positive components (P50, P100 and P300) in patients with BPD, which could provide information in the detection of altered neural correlates in attention deficit processing, impulsivity and psychotic susceptibility. Unoka and Richman (2016) conclude that cognitive impairment is what distinguishes patients with BPD compared to the control group. Impairment that is present in processes associated with decision-making, memory, difficulty in changing mental state, response inhibition and planning, relating to impulsivity, self-injury, dissociative symptoms and emotional dysregulation (Unoka & Richman, 2016).

The meta-regression analyses analyzed the percentage of women, Gini, and GDP. It was observed that the percentage of women and GDP had no significant effect. However, the Gini, which measures economic inequality, did have a significant effect as a moderating variable. The literature has indicated that optimal access to economic resources is considered a protective factor for emotional, social, and financial burden, but when inequality exists, this factor interacts with neurobiological mechanisms associated with trauma (Harnett et al., 2023). Furthermore, it has been observed that in impoverished urban environments BPD symptoms is higher (García et al., 2010). This is consistent with new theories on the psychological impact of traumatic events (Leiva-Bianchi et al., 2018) and recent findings on PTSD symptoms (Cáceres et al., 2022).

Regarding the evaluation of potential biases in the study, the indicators showed good results. However, Z_{Egger} was significant. This can be explained by the values reported in Ramos-Loyo et al. (2021) where a small sample ($N = 11$) and a very high correlation ($r = .85$) can be observed.

Therefore, the P300 component could be considered for use as a possible biomarker to identify altered neural correlates in BPD. The present meta-analysis supports the proposition that an altered P300 would be present in disorders related to exposure to traumatic events such as BPD. Adverse events during childhood and prenatally have been identified as being involved in the development of altered cognitive processes, emotional dysregulation, impulsivity, and dysfunctional behaviours (Lieb et al., 2004; Palumbo et al., 2018). However, a distinct neural correlate between BPD, PTSD, CPTSD has not yet been established (Azcárate et al., 2017).

The relationship found between P300 and BPD symptoms could be used as an indicator of improvement in therapeutic processes, because it is possible to observe through the learning of cognitive skills, an improvement in cognitive processes related to BPD clinical symptoms (Unoka & Richman, 2016; Vai et al., 2021). This would be possible to achieve using effective therapies, such as, Dialectical Behavior Therapy (DBT), Mentalization Therapy, Eye Movement Desensitization and Reprocessing (Bradley et al., 2005; Choi-Kain et al., 2021; Ehring et al., 2014; Watts et al., 2013).

The limitations of this study lie in the diversity of methods and samples used. The selected articles used different paradigms or tasks during ERP measurements. The symptoms assessed also varied (e.g. risk-taking decisions, impulsivity, emotion dysregulation and global BPD symptoms). The number of meta-analyzable studies made it impossible to control for these sources of variability. Finally, further studies with event-related potentials are recommended to determine what other ERP components might exhibit BPD-associated symptoms and to determine whether other potential biomarkers might exist.

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Author contribution

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Data availability statement

The data that support the findings of this study are openly available in 'Mendeley Data' at http://doi.org/10.17632/m69dtg9vb6.1.

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