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Research Paper

Early parental mental health and postnatal bonding as predictors of neurodevelopmental outcomes in very preterm or very low birth weight infants: A three-year prospective study

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ABSTRACT

Background: Infants born very preterm (VPT) or with very low birth weight (VLBW) are at increased risk of neurodevelopmental difficulties. While biomedical predictors have been extensively studied, less is known about early psychosocial factors, particularly parental mental health and postnatal bonding.
Aim: This study examined parental mental health, postnatal bonding, sociodemographic, and biomedical predictors of neurodevelopment during the first three years in VPT/VLBW infants.
Methods: This prospective longitudinal study included 114 VPT/VLBW infants and their parents. Predictors included neonatal, sociodemographic, and obstetric factors, as well as psychopathology, postpartum depression, anxiety, and postnatal bonding, assessed during the neonatal intensive care unit (NICU) stay. Neurodevelopment was assessed at 12, 24, and 36 months using the Bayley Scales of Infant and Toddler Development, Third Edition. Linear mixed-effects models were fitted for cognitive, receptive and expressive language, and fine and gross motor domains.
Results: Greater partner phobic anxiety and maternal postnatal bonding difficulties were associated with poorer cognitive and language outcomes. Maternal interpersonal sensitivity was negatively associated with expressive language, whereas maternal paranoid ideation was associated with poorer fine motor outcomes. Maternal foreign origin was associated with poorer language outcomes. Among biomedical factors, infant female sex was associated with better fine motor outcomes, longer NICU stay with poorer gross motor outcomes, and higher 5-min Apgar scores with better receptive language outcomes.
Conclusions: Neurodevelopment in VPT/VLBW infants was associated with both biomedical and psychosocial factors. Findings highlight the relevance of parental mental health and postnatal bonding, supporting an integrative approach to early monitoring and support.

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1. Introduction

Preterm birth, particularly in very preterm (VPT; <32 weeks of gestation) and very low birth weight (VLBW; <1500 g) infants, is associated with increased biological vulnerability, characterized by brain immaturity and a heightened susceptibility to neurodevelopmental difficulties [1–5]. In addition, preterm birth is associated with increased psychopathological symptoms in both parents [6,7], which may, in turn, have implications for the early caregiving environment and infant neurodevelopment [8,9]. In this context, neurodevelopment in VPT/VLBW infants should be conceptualized within a biopsychosocial framework that integrates initial biological vulnerability with early family psychosocial conditions [10]. This perspective is consistent with ecological models of development, which emphasize the dynamic interaction between the infant and their environment [11,12].

Evidence indicates that VPT/VLBW infants are at increased risk of neurodevelopmental difficulties across cognitive, language, and motor domains compared to full-term infants [13–15]. These difficulties are associated with alterations in multiple brain regions [3,4]. However, despite evidence of this increased risk, substantial interindividual variability in neurodevelopmental trajectories persists during the first years of life [16].

This heterogeneity in neurodevelopmental trajectories underscores the need to identify early predictors that may help to understand the underlying mechanisms and to inform interventions targeting potentially modifiable factors. In this context, the literature primarily distinguishes between biomedical and psychosocial predictors, and highlights the importance of considering both types of factors jointly to achieve a more comprehensive understanding of neurodevelopment in preterm infants [16,17]. Among biomedical factors with the strongest empirical support are perinatal characteristics such as male sex [17–20], and lower gestational age and birth weight [21–25]. Clinical indicators, including lower Apgar scores at 5 min and longer hospital stay [3,21,26–29], as well as markers of brain injury and early structural brain vulnerability [17,21,30,31], have also been associated with an increased risk of neurodevelopmental delays.

Among psychosocial predictors of neurodevelopment in preterm infants, socioeconomic status (SES) is one of the factors with the strongest empirical support, particularly low maternal education [22,24,28,32,33], as well as poverty [17,25,34,35]. Additionally, other relevant factors have been identified, such as early stimulation in the home environment [28,36], the quality of the home environment [24], and maternal foreign origin [19].

Regarding early parental mental health as a predictor of neurodevelopment, the evidence shows inconsistent findings. In the NICU setting, parental psychological symptoms may be understood within the context of neonatal hospitalization, where parental role alteration has been identified as an important source of stress and may have implications for later child developmental outcomes [37]. In preterm populations, several studies have reported that maternal anxiety during the NICU stay is associated with poorer outcomes in the cognitive [38], language [9], and fine motor domains [39]. Similarly, postpartum depression has been associated with poorer cognitive outcomes [8,40,41] and with difficulties in overall neurodevelopment [42]. However, other studies have not found significant associations [43]. Overall, the available evidence remains limited due to the small number of studies, the limited inclusion of fathers, and the predominance of research focusing exclusively on anxiety and depression. In this context, the relationship between other specific psychopathological symptoms and child development remains unclear [44]. In the general population, specific dimensions such as paranoid ideation, hostility, psychoticism, somatization, and interpersonal sensitivity have been shown to influence different domains of child development [44–47]. These findings suggest that, even in the absence of a psychiatric diagnosis, subclinical parental symptomatology may influence child development.

In addition to parental mental health, postnatal bonding is a key process during the postpartum period [48,49]. Postnatal bonding refers to the emotional, behavioral, and cognitive tie that parents develop after birth [49–52]. In the general population, several studies have shown that bonding difficulties are associated with poorer developmental outcomes in children, including socioemotional difficulties, increased temperamental reactivity, and difficulties in executive functioning [53–58]. However, the available evidence remains limited [54,56], and no studies have specifically examined postnatal bonding as a predictor of neurodevelopment in preterm populations, particularly in studies including both parents.

These psychosocial factors, as described above, in addition to their role as risk factors for neurodevelopment, have also been shown to influence brain structure in preterm infants [16,22], and may moderate the relationship between the development of specific brain structures and different domains of infant neurodevelopment [22,59].

Overall, the available evidence underscores the need for longitudinal studies that integrate biomedical and psychosocial predictors to explain neurodevelopmental trajectories in VPT/VLBW infants. In addition, it is particularly important to include both parents and to consider parental mental health and postnatal bonding as early predictors of neurodevelopment.

Accordingly, the present study aims to examine biomedical and psychosocial predictors of neurodevelopmental trajectories across cognitive, language (receptive and expressive), and motor (fine and gross) domains in VPT/VLBW infants between 12 and 36 months of age.

2. Methods

2.1. Study design and procedure

This prospective observational study was conducted within a larger longitudinal research project on very preterm birth at Donostia University Hospital. Families of VPT/VLBW infants were recruited between 2018 and 2021.

Families were recruited during the infant's NICU hospitalization by a neonatologist who was a member of the research team. After written informed consent was obtained, both parents completed a set of questionnaires during the first month of the infant's NICU hospitalization. These assessments constituted the baseline measures of the predictor variables, including neonatal, sociodemographic, obstetric, parental mental health, and postnatal bonding.

Infant neurodevelopment was assessed longitudinally at 12, 24, and 36 months by the same trained members of the research team. Assessments at 12 and 24 months were conducted using corrected age, whereas the 36-month assessment was conducted using chronological age, in accordance with standard clinical practice in the follow-up of preterm infants.

The study was approved by the Clinical Research Ethics Committee of the Gipuzkoa Health Area (code: MOR-PRE-2018-01).

2.2. Participants

The study sample consisted of 114 VPT/VLBW infants and their parents, including 101 mothers and 97 partners.

The inclusion criteria were: (a) gestational age $\leq$ 32 weeks and/or birth weight $\leq$ 1500 g, (b) a NICU stay longer than 14 days, and (c) sufficient parental proficiency in Spanish to complete the self-report measures.

The study sample included two same-sex female couples. Accordingly, the term *partner* is used throughout the manuscript to refer to the non-birthing parent, ensuring consistent and inclusive terminology across different family structures.

2.3. Measures

2.3.1. Predictor variables

2.3.1.1. Neonatal variables. The following neonatal variables were collected: sex, birth weight, gestational age, head circumference at birth, birth length, 1-min Apgar score, 5-min Apgar score, and length of NICU stay.

2.3.1.2. Parental sociodemographic and obstetric characteristics. For each parent, the following sociodemographic variables were collected: age, educational level, income level, marital status, and cohabitation status. Obstetric variables were also collected, including parity, type of pregnancy and delivery, multiple gestation, difficulty conceiving, and history of miscarriage.

2.3.1.3. Parental mental health measures. In both parents, general psychopathological symptoms, postpartum depression, and anxiety were assessed. All measures were analyzed as continuous variables.

2.3.1.3.1. General psychopathological symptoms. The *Symptom Checklist-90-Revised* (SCL-90-R) [60] was used to assess general psychopathological symptoms. It comprises 90 items rated on a 5-point Likert scale (0–4), with higher scores indicating greater symptom severity in each dimension. Items are grouped into nine primary symptom dimensions: Somatization, Obsessive–Compulsive, Interpersonal Sensitivity, Depression, Anxiety, Hostility, Phobic Anxiety, Paranoid Ideation, and Psychoticism. The Global Severity Index (GSI) was used as an indicator of overall psychological distress. The Spanish validated version was used [61], with Cronbach's alpha coefficients ranging from 0.81 to 0.90 across dimensions.

2.3.1.3.2. Postpartum depression. The *Edinburgh Postnatal Depression Scale* (EPDS) [62] was used to assess postpartum depressive symptoms. The EPDS includes 10 items rated on a 4-point scale (0–3), yielding a total score ranging from 0 to 30, with higher scores indicating greater symptom severity. The Spanish validated version was used [63], showing adequate internal consistency ($\alpha = 0.79$). Although analyses were conducted using continuous scores, a cutoff of $\geq$10 was used for descriptive purposes, indicating clinically relevant depressive symptoms [63].

2.3.1.3.3. Anxiety. The *State–Trait Anxiety Inventory* (STAI) [64] was used to assess two dimensions of anxiety: State Anxiety and Trait Anxiety. The STAI consists of 40 items across two 20-item subscales, rated on a 4-point scale (0–3), yielding total scores ranging from 0 to 60, with higher scores indicating greater symptom severity. The Spanish validated version was used [65], which showed excellent internal consistency for both subscales: State Anxiety ($\alpha = 0.94$) and Trait Anxiety ($\alpha = 0.90$).

2.3.1.4. Postnatal bonding measures. Postnatal bonding was assessed using the *Postpartum Bonding Questionnaire* (PBQ) [66], designed to detect bonding difficulties. The PBQ comprises 25 items rated on a 6-point Likert scale (0–5), yielding total scores ranging from 0 to 125, with higher scores indicating greater bonding difficulties. The Spanish validated version was used [51], showing excellent internal consistency ($\alpha = 0.90$). Although continuous scores were used in the analyses, a cutoff score of $\geq$19 was used for descriptive purposes, indicating possible bonding disorders [67].

2.3.2. Outcome variables

2.3.2.1. Neurodevelopmental outcomes. Infant neurodevelopment was assessed using the Spanish version of the Bayley Scales of Infant and Toddler Development, Third Edition [68], a standardized instrument that evaluates cognitive, language, and motor development in infants aged 16 days to 42 months. In the present study, scaled scores (mean = 10, SD = 3) were used rather than broader composite scores to allow a more domain-specific analysis of the cognitive, receptive language, expressive language, fine motor, and gross motor domains, in line with the aim of identifying potentially distinct predictor patterns across developmental domains. These scores allow comparisons with age-adjusted normative data. The Bayley-III has demonstrated strong reliability and validity for the assessment of early development [68].

2.4. Statistical analysis

Descriptive analyses were conducted to characterize the sample. Continuous variables were summarized using means and standard deviations, and categorical variables using frequencies and percentages.

To examine predictors of neurodevelopment, separate linear mixed-effects models (LMMs) [69,70] were fitted for each domain: cognition, receptive language, expressive language, fine motor, and gross motor. These models appropriately account for the longitudinal data structure, in which each infant contributes multiple correlated observations. Time (12, 24, and 36 months) and predictor variables – including neonatal characteristics, sociodemographic and obstetric variables, as well as parental mental health and postnatal bonding – were included as fixed effects. A random intercept for infant was included to account for within-subject correlation arising from repeated measures and to capture unobserved heterogeneity between individuals. Random intercepts were assumed to follow a normal distribution and to be independent of the residual error term. LMMs allow the use of all available longitudinal outcome data, thereby enabling the inclusion of participants with incomplete Bayley-III data at some assessment time points under the assumption that outcome data are missing at random (MAR). Missing data in baseline predictors were handled using model-specific complete-case analyses.

Predictor variables were selected based on clinical plausibility and prior evidence. Given the number of potential predictors relative to the sample size, a two-stage modelling strategy was used to reduce the predictor space before fitting the final multivariable models. First, univariable analyses were conducted separately for each Bayley-III outcome domain, and variables associated with each outcome at $p < 0.10$ were retained for the second stage. Second, variables retained after univariable screening were entered into multivariable models, and backward stepwise selection based on the Akaike Information Criterion (AIC) was applied. AIC-based selection was used to balance model goodness-of-fit and parsimony. The absence of substantial multicollinearity among predictors in the final models was assessed using adjusted generalized variance inflation factors (GVIFs), with values below 5 considered acceptable. Model stability was further examined using a bootstrap resampling sensitivity analysis with 500 iterations, in which the two-stage variable selection procedure was repeated in each bootstrap sample.

For each final model, estimates of the fixed effects ($\widehat{\beta}$) – that is, the regression coefficients associated with the predictor variables – along with their 95% confidence intervals and *p*-values, were reported. In addition, estimates of the residual variance ($\widehat{\sigma}^2$), the variance of the random intercept ($\widehat{\tau}^2$), and the intraclass correlation coefficient (ICC) were reported to quantify the proportion of total variance attributable to between-subject variability. Assumptions of normality and homoscedasticity of residuals were evaluated through graphical inspection.

All statistical analyses were performed using the open-source statistical software R version 4.4.1 [71], with a statistical significance level set at 5%. Specifically, the *tidyverse* [72] and *ggplot2* [73] packages were used for data handling and data visualization, the *rstatix* [74] package was used for the initial descriptive statistical and inferential analyses, and the *lme4* [75] package was used for fitting linear mixed-effects models. The analysis code is publicly available at: https://github.com/lzumeta/preterm_neurodevelopment.

3. Results

3.1. Sample characteristics

The sample consisted of 114 VPT/VLBW infants (63 males and 51 females) and their parents (101 mothers and 97 partners). Analyses involving parental psychopathology and postnatal bonding were based on the subsample of mothers ($n = 87$) and partners ($n = 77$) who completed the relevant questionnaires (see Supplementary Fig. 1).

Neonatal characteristics included a mean birth weight of 1237.32 g and a mean gestational age of 29.57 weeks. Apgar scores averaged 6.61 at 1 min and 8.30 at 5 min, and the mean length of NICU stay was 55.97 days.

Regarding sociodemographic variables, the mean age was 34.81 years for mothers and 37.08 years for partners. Most parents were of Spanish nationality, although a substantial proportion were of foreign origin. Secondary education was the most common educational level, followed by university education. The majority of parents were married or in a stable relationship and cohabiting. In terms of annual income, a higher proportion of mothers reported low income (<€15,000), whereas partners more frequently reported middle-income levels (€15,000–30,000).

With respect to obstetric variables, 57.4% of mothers were primiparous. Most pregnancies were spontaneous (63.4%), whereas 26.7% involved assisted reproductive technologies. Caesarean section accounted for 67.3% of deliveries. Furthermore, 30.7% of mothers reported difficulties conceiving, and 49.5% reported a history of previous miscarriages (see Table 1).

Descriptive statistics for parental mental health (EPDS, STAI, and SCL-90-R) and postnatal bonding (PBQ) are presented in Supplementary Table 1. Overall, 63.2% of mothers ($n = 55$) and 27.3% of partners ($n = 21$) scored at or above the EPDS cutoff, indicating clinically relevant depressive symptoms. In contrast, postnatal bonding difficulties were relatively uncommon, with scores at or above the PBQ cutoff observed in 8.6% of maternal PBQ assessments ($n = 8$) and 10.1% of partner PBQ assessments ($n = 8$). Additional distributional characteristics of the SCL-90-R dimensions are provided in Supplementary Table 2.

Neurodevelopmental outcomes, including descriptive statistics and available Bayley-III outcome data at each follow-up assessment, are presented in Supplementary Table 3. Bayley-III scaled scores across the cognitive, receptive language, expressive language, fine motor, and gross motor domains varied across domains and time points, with means ranging from 8.0 to 10.4.

Comparisons between infants with complete and incomplete follow-up data are presented in Supplementary Tables 4 and 5. No statistically significant differences were observed in neonatal characteristics or parental mental health and postnatal bonding variables. However, among sociodemographic variables, maternal country of origin differed between groups, with a higher proportion of mothers of foreign origin among infants with incomplete follow-up data ($p = 0.021$).

3.2. Early predictors of neurodevelopment in VPT/VLBW infants

Predictors of each neurodevelopmental domain were examined using linear mixed-effects models (LMMs) with random intercepts for infants and the two-stage variable selection procedure described above. Due to missing data in baseline predictors, final analytical sample sizes varied across outcome-specific models: 71 infants for cognition, 70 for receptive language, 70 for expressive language, 86 for fine motor, and 101 for gross motor.

Adjusted GVIF values for all predictors retained in the final models were below 5, suggesting that multicollinearity was not a major concern. In the bootstrap sensitivity analysis, selection frequencies for retained predictors ranged from 20.2% to 79.0%, indicating that some predictors were relatively stable, whereas others were more sensitive to sampling variability. Multicollinearity diagnostics and bootstrap selection frequencies are presented in Supplementary Table 6.

3.2.1. Cognition

In the cognitive domain, a significant effect of time was observed, with higher scores at 36 months compared to the 12-month reference assessment ($\widehat{\beta} = 0.85$, $p = 0.044$). Partner phobic anxiety ($\widehat{\beta} = -2.81$, $p < 0.001$) and greater maternal postnatal bonding difficulties ($\widehat{\beta} = -0.09$, $p = 0.017$) were negatively associated with cognitive scores.

The marginal R^2 was 0.143 and the conditional R^2 was 0.425. That is, fixed effects explained 14.3% of the variance, increasing to 42.5% when random effects were included. The ICC was 0.33, indicating that approximately one-third of the total variance was attributable to differences between individuals (see Fig. 1).

3.2.2. Receptive language

In the receptive language domain, significant increases in scores were observed at 24 months ($\widehat{\beta} = 0.95$, $p = 0.013$) and 36 months ($\widehat{\beta} = 1.77$, $p < 0.001$) compared to the 12-month reference assessment. Partner phobic anxiety ($\widehat{\beta} = -2.98$, $p < 0.001$) and greater maternal postnatal bonding difficulties ($\widehat{\beta} = -0.09$, $p = 0.039$) were associated with lower scores in this domain. Maternal foreign origin was also negatively associated with receptive language scores ($\widehat{\beta} = -1.27$, $p = 0.043$), whereas higher Apgar scores at 5 min were associated with higher receptive language scores ($\widehat{\beta} = 0.46$, $p = 0.035$).

The model explained 24.1% of the variance through fixed effects and 49.7% when random effects were included. The ICC was 0.34 (see Fig. 2).

3.2.3. Expressive language

In the expressive language domain, no significant time effects were observed. Partner phobic anxiety ($\widehat{\beta} = -2.79$, $p < 0.001$), greater maternal postnatal bonding difficulties ($\widehat{\beta} = -0.09$, $p = 0.020$), and maternal foreign origin ($\widehat{\beta} = -1.48$, $p = 0.006$) were associated with lower scores in this domain. In addition, higher maternal interpersonal sensitivity was associated with lower expressive language scores ($\widehat{\beta} = -0.74$, $p = 0.046$).

The model explained 18.7% of the variance through fixed effects and 32.6% when random effects were included. The ICC was 0.17 (see Fig. 3).

3.2.4. Fine motor

In the fine motor domain, no significant time effects were observed. Female sex was associated with higher fine motor scores ($\widehat{\beta} = 1.10$, $p = 0.003$). In contrast, higher levels of maternal paranoid ideation were associated with lower scores ($\widehat{\beta} = -1.01$, $p = 0.007$).

The model explained 10.8% of the variance through fixed effects and 23.8% when random effects were included. The ICC was 0.15 (see Fig. 4).

3.2.5. Gross motor

In the gross motor domain, scores were significantly higher at 36 months compared to the 12-month reference assessment ($\widehat{\beta} = 1.50$, $p < 0.001$). Longer NICU stay was associated with lower scores in this domain ($\widehat{\beta} = -0.03$, $p = 0.001$).

The model explained 10.2% of the variance through fixed effects and 48.7% when random effects were included. The ICC was 0.43, indicating that a substantial proportion of the total variance was attributable to differences between individuals (see Fig. 5).

4. Discussion

The present study longitudinally examined the contribution of biomedical and psychosocial factors to neurodevelopmental trajectories

Table 1
Sociodemographic, obstetric, and neonatal characteristics of the study sample.

	Mothers (n = 101)	Partners (n = 97)
Panel A. Sociodemographic characteristics		
Age (years)	34.81 (5.54)	37.08 (5.95)
Education level		
Primary education or less	6 (5.9%)	6 (6.2%)
Secondary education	44 (43.6%)	50 (51.5%)
University degree	26 (25.7%)	12 (12.4%)
Postgraduate education	11 (10.9%)	9 (9.3%)
Missing values	14 (13.9%)	20 (20.6%)
Marital status		
Married	51 (50.5%)	51 (52.6%)
In a relationship	41 (40.6%)	40 (41.2%)
Single	4 (4.0%)	0 (0.0%)
Missing values	5 (5.0%)	6 (6.2%)
Cohabitating		
Yes	90 (89.1%)	90 (92.8%)
No	5 (5.0%)	1 (1.0%)
Missing values	6 (5.9%)	6 (6.2%)
Annual income (€)		
Low income (<15,000)	42 (41.6%)	17 (17.5%)
Medium income (15,000 – 〈30,000)	28 (27.7%)	38 (39.2%)
High income (≥ 30,000)	8 (7.9%)	21 (21.65%)
Missing values	23 (22.8%)	21 (21.65%)
Nationality		
Spanish nationality	67 (66.3%)	67 (69.1%)
Non-Spanish nationality	31 (30.7%)	22 (22.7%)
Missing values	3 (3.0%)	8 (8.2%)
Same-sex couple		
Yes	2 (2.0%)	0 (0.0%)
No	99 (98.0%)	97 (100%)
Panel B. Obstetric and reproductive characteristics		
Parity		
Primiparous	58 (57.4%)	
Multiparous	42 (41.6%)	
Missing values	1 (1.0%)	
Pregnancy type		
Spontaneous	64 (63.4%)	
Assisted reproduction	27 (26.7%)	
Missing values	10 (9.9%)	
Multiple pregnancy		
Yes	16 (15.8%)	
No	84 (83.2%)	
Missing values	1 (1.0%)	
Mode of delivery		
Vaginal	29 (28.7%)	
Caesarean	68 (67.3%)	
Missing values	4 (4.0%)	
Difficulty conceiving		
Yes	31 (30.7%)	
No	58 (57.4%)	
Missing values	12 (11.9%)	
Previous miscarriages		
Yes	50 (49.5%)	
No	47 (46.5%)	
Missing values	4 (4.0%)	

	Infants (n = 114)	N total
Panel C. Neonatal variables		
Infant sex		114
Male	63 (55.3%)	
Female	51 (44.7%)	
Birth weight (g)	1237.32 (340.07)	114
Gestational age (weeks)	29.57 (2.51)	114
Head circumference at birth (cm)	27.0 (2.51)	109
Birth length (cm)	38.50 (3.63)	111
1-min Apgar score	6.61 (1.93)	114
5-min Apgar score	8.29 (1.29)	114
NICU stay (days)	55.97 (26.72)	112

Note. Continuous variables are presented as mean (SD). Categorical variables are presented as n (%).

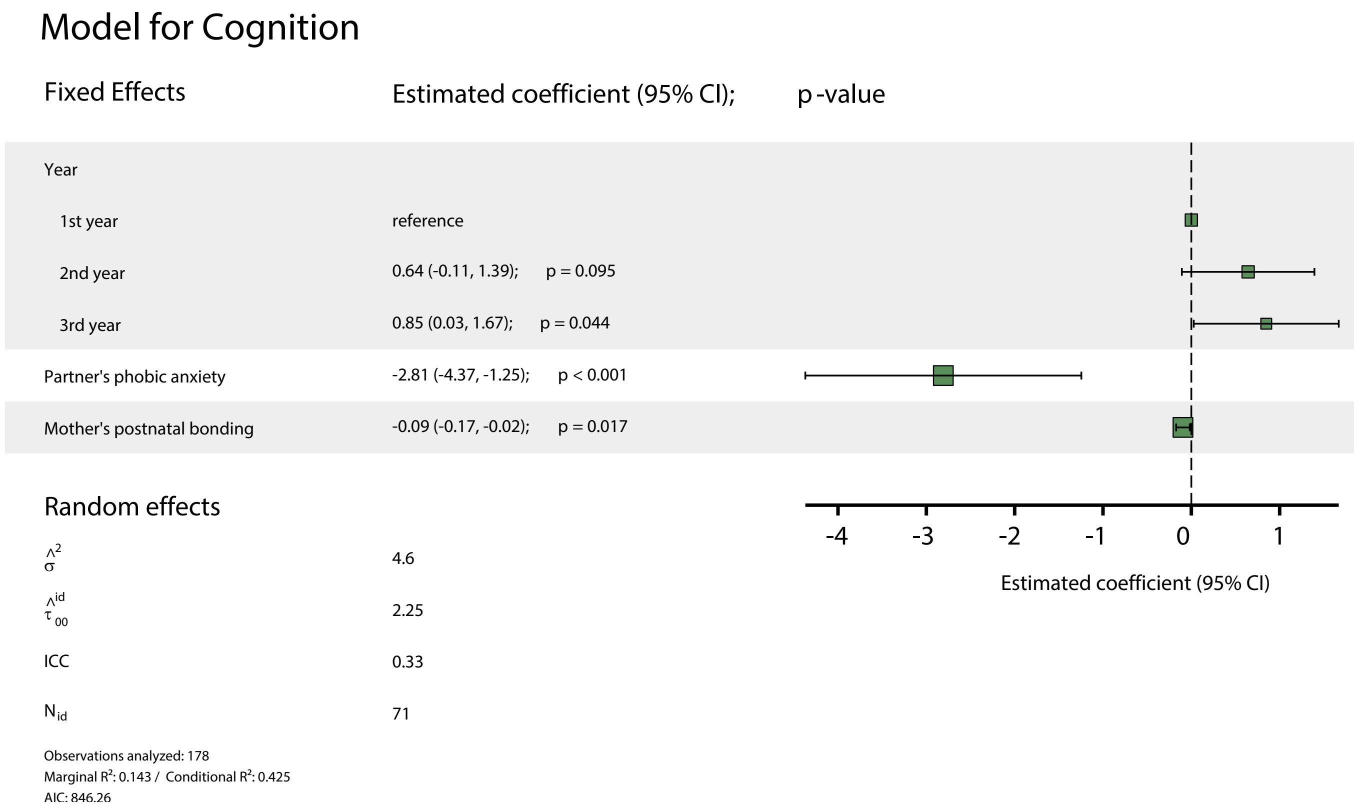

Fig. 1. Forest plot showing the results of the linear mixed-effects model for the cognition domain of infant neurodevelopment.

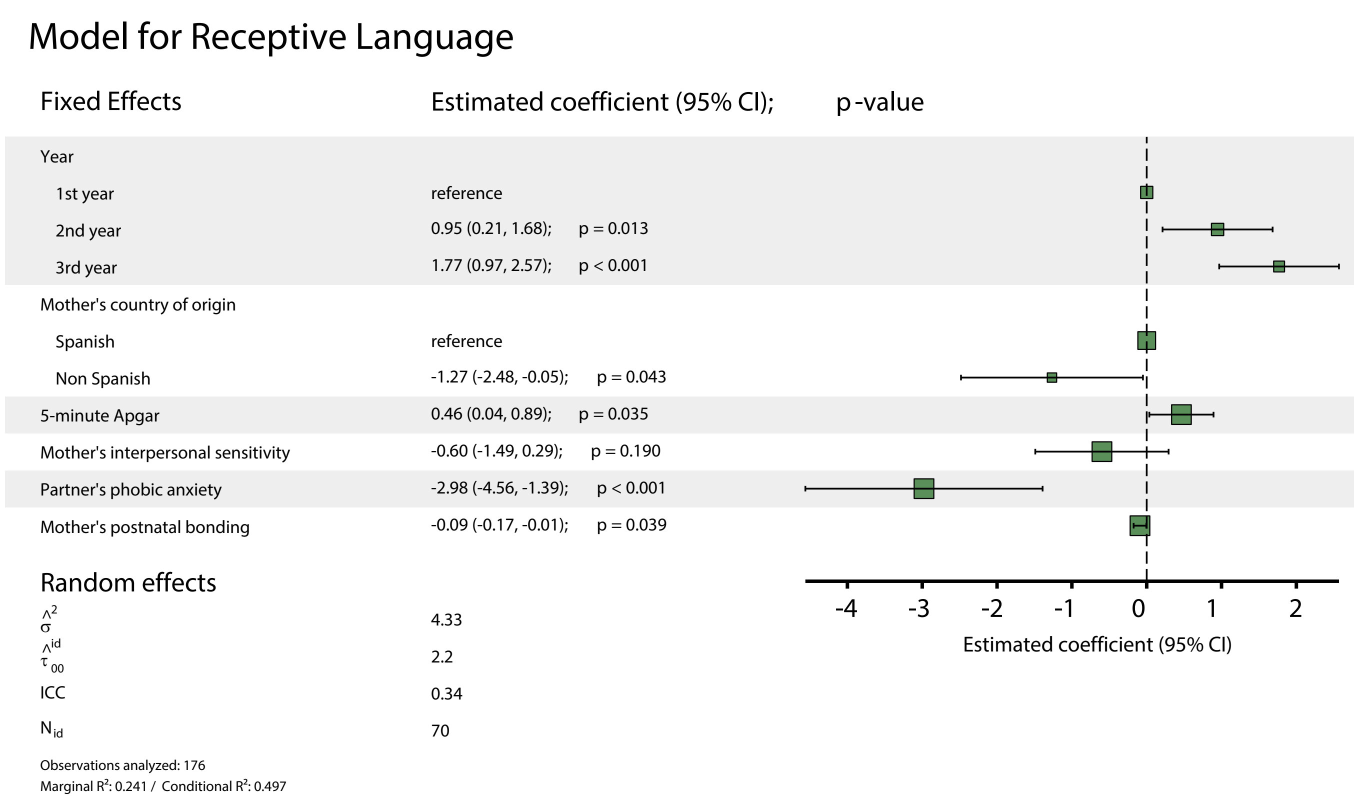

Fig. 2. Forest plot showing the results of the linear mixed-effects model for the receptive language domain of infant neurodevelopment.

in VPT/VLBW infants during the first three years of life. Overall, the findings indicate that both biomedical and psychosocial factors jointly contributed to explaining variability in neurodevelopmental trajectories. In addition, the observed interindividual variability highlights

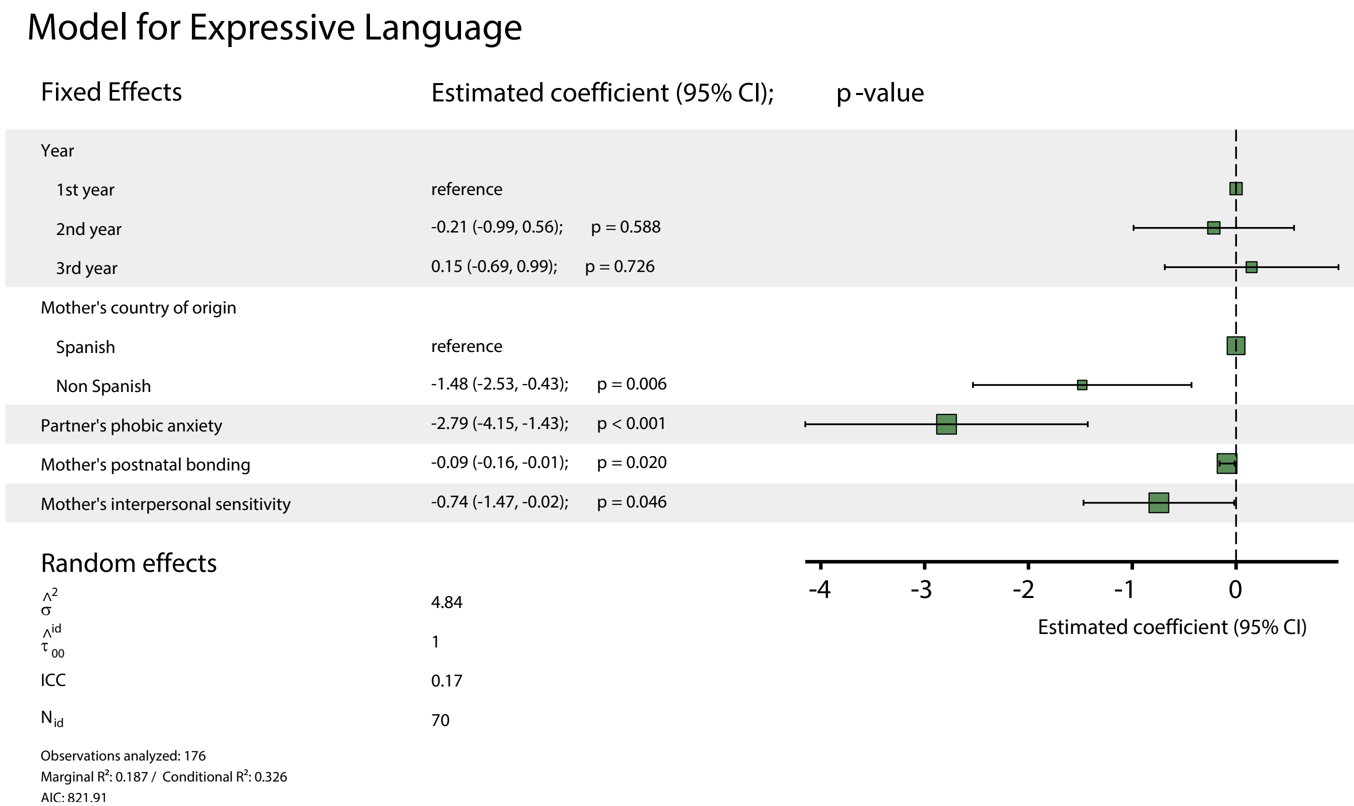

Fig. 3. Forest plot showing the results of the linear mixed-effects model for the expressive language domain of infant neurodevelopment.

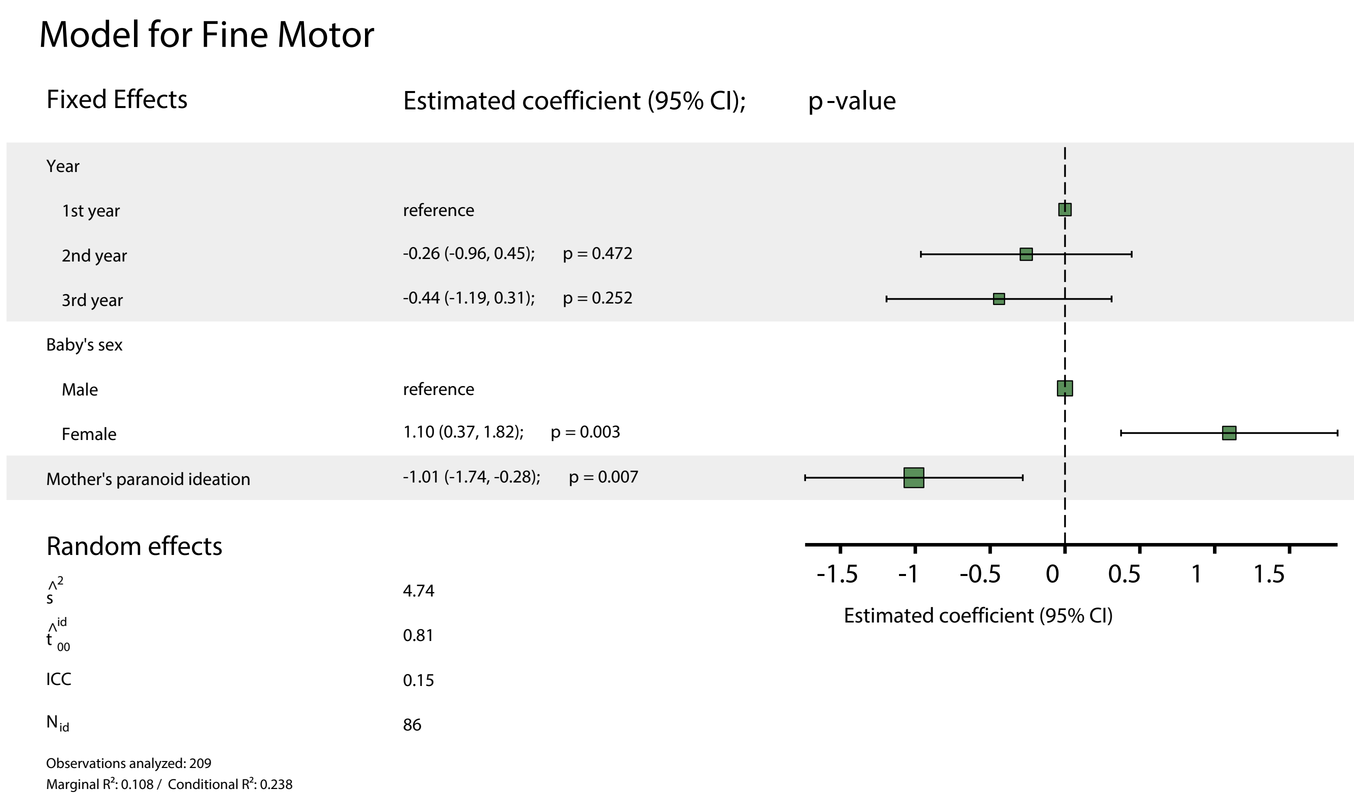

Fig. 4. Forest plot showing the results of the linear mixed-effects model for the fine motor domain of infant neurodevelopment.

the heterogeneous and multifactorial nature of neurodevelopment in this vulnerable population.

Furthermore, domain-specific patterns were observed in the associations between predictors and neurodevelopmental outcomes.

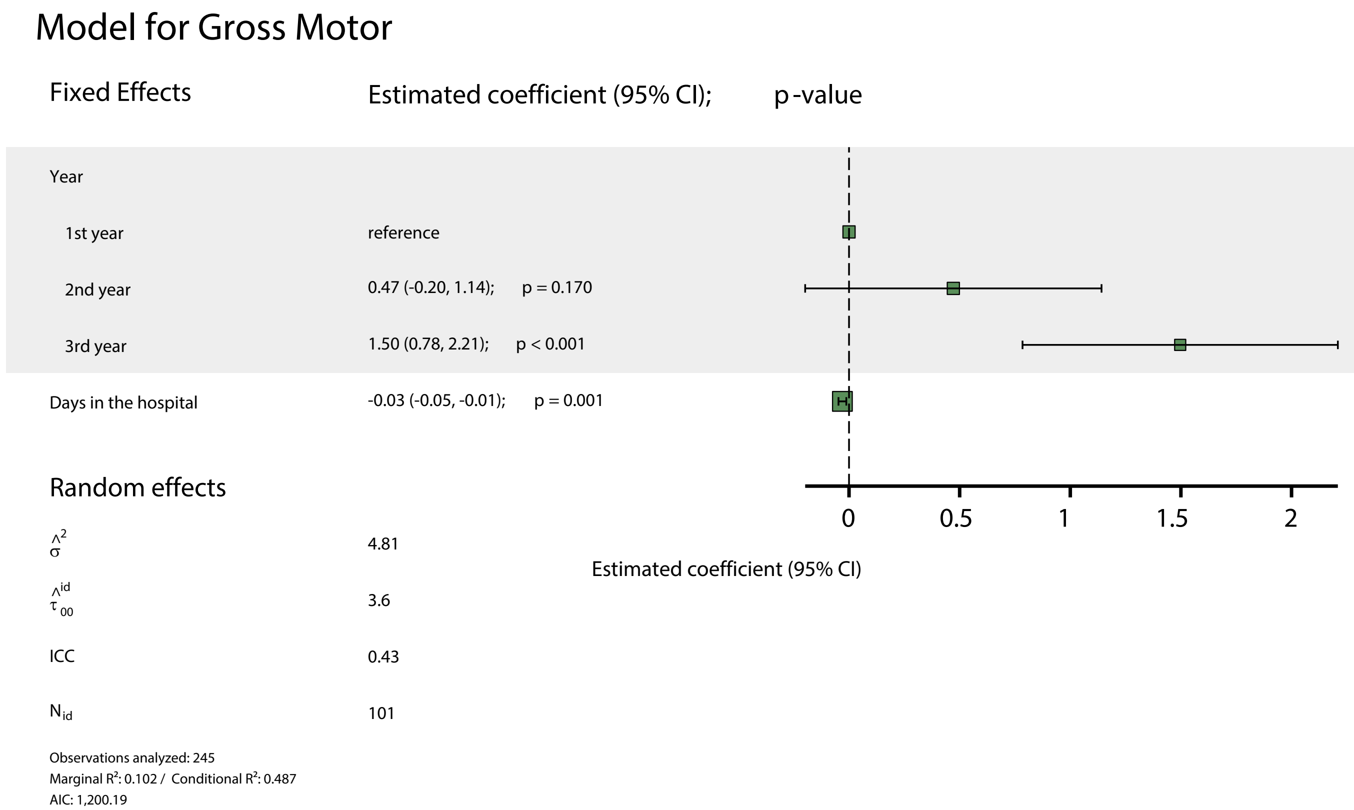

Fig. 5. Forest plot showing the results of the linear mixed-effects model for the gross motor domain of infant neurodevelopment.

Specifically, psychosocial factors were primarily associated with cognitive and language domains, whereas biomedical factors were mainly associated with motor development. This pattern is consistent with previous studies reporting differential contributions of distinct types of predictors depending on the developmental domains assessed [19,76,77].

4.1. *Psychosocial predictors*

The present findings indicate that psychosocial factors helped explain interindividual variability in neurodevelopmental trajectories among VPT/VLBW infants, with associations differing across developmental domains during the first three years of life. This pattern is consistent with ecological models of development, which emphasize the dynamic interaction between biological vulnerability and the early psychosocial environment [11,12].

In this context, parental mental health emerged as a particularly relevant factor, as it was consistently associated with cognitive, language, and fine motor domains in VPT/VLBW infants. Specifically, partner phobic anxiety, characterized by avoidance behaviors, was associated with poorer cognitive and language outcomes. Likewise, maternal interpersonal sensitivity, characterized by inhibition in interpersonal relationships, was associated with poorer expressive language outcomes, whereas maternal paranoid ideation, characterized by suspiciousness toward others, was associated with poorer fine motor outcomes. To our knowledge, these specific dimensions have not been previously examined as predictors of neurodevelopment in preterm populations. Nevertheless, these findings are consistent with studies in the general population highlighting the role of specific dimensions of psychological adjustment in different domains of neurodevelopment [44,46,47]. Further research is needed to confirm the role of these specific psychopathological dimensions in infant neurodevelopment.

These findings can be interpreted within the framework of Belsky's model [11], which conceptualizes parenting behavior and child development as shaped by parental characteristics, child characteristics, and the broader social context. Within this framework, dimensions such as phobic anxiety, interpersonal sensitivity, and paranoid ideation may be relevant to parental behavior and the early caregiving context, thereby providing a conceptual basis for understanding their prospective associations with neurodevelopment in VPT/VLBW infants. This interpretation is also consistent with evidence showing that NICU-related stress, including parental role alteration, is associated with later child developmental outcomes [37]. However, these potential mediating or moderating pathways were not formally tested in the present study and should therefore be examined in future research. Overall, these results extend previous literature, which has traditionally focused on anxiety and postpartum depression, by highlighting the potential relevance of other, more specific dimensions of parental psychological adjustment. In this regard, it is noteworthy that traditional indicators of anxiety and depression were not retained in the final models, in line with previous findings [43], despite earlier evidence suggesting their relevance [8,9,38–42].

Similarly, maternal postnatal bonding was associated with infant neurodevelopment, specifically in the cognitive and language domains. To date, postnatal bonding has rarely been examined as a predictor of neurodevelopment in preterm populations. However, these findings are consistent with studies in the general population linking difficulties in postnatal bonding with poorer developmental outcomes in children [53–57].

Regarding sociodemographic factors, maternal foreign origin was negatively associated with language development, in line with previous studies in very preterm populations [19,78]. This finding should not be interpreted as a causal effect of maternal foreign origin itself, but may rather reflect the interplay of socioeconomic, contextual, cultural, and language exposure factors that were not directly measured in the present study. In contrast, widely studied variables such as parental educational level and socioeconomic status were not retained as predictors in the final models, consistent with some previous studies [79], despite prior evidence demonstrating their association with neurodevelopment in preterm populations [22,24,28,32,33,76]. This discrepancy in findings may be related to the simultaneous inclusion of early environmental factors, such as parental mental health and postnatal bonding, which may modify the contribution of sociodemographic variables within the explanatory models.

4.2. Biomedical predictors

Regarding biomedical factors, several neonatal variables showed domain-specific associations with fine and gross motor development, as well as with receptive language. Infant female sex was associated with better fine motor outcomes, in line with previous evidence describing greater male vulnerability following preterm birth [18–20,77].

Similarly, longer NICU stay was associated with poorer gross motor outcomes, consistent with previous studies [28,29,36]. This finding may be explained by the fact that longer hospitalization often reflects greater neonatal severity or clinical complexity, as well as reduced opportunities for early stimulation in the hospital setting, particularly in the motor domain, compared with the home environment [29,36].

In turn, higher 5-min Apgar scores were associated with better receptive language outcomes, in line with the literature identifying low Apgar scores as a predictor of poorer neurodevelopmental outcomes, including motor [28], cognitive, and language difficulties [26,27].

Overall, biomedical factors were prospectively associated with a more limited number of neurodevelopmental domains compared to psychosocial factors. This should be interpreted with caution, given that more specific neonatal clinical indicators, previously identified as relevant for neurodevelopment in preterm populations, were not included in the present study [26].

4.3. Integrative interpretation of findings

From an integrative perspective, the findings of the present study can be interpreted within the framework of Belsky's model of the determinants of parenting [11], which conceptualizes child development as the joint contribution of child characteristics, parental characteristics, and contextual factors. Within this framework, the identified biomedical factors (infant sex, Apgar score, and length of NICU stay) can be situated at the level of child characteristics; parental mental health and postnatal bonding correspond to parental characteristics, and sociodemographic variables, such as maternal origin, to contextual factors. Overall, these findings reinforce the need to adopt an integrative approach to the study of neurodevelopment in VPT/VLBW infants, one that considers both initial biological vulnerability and early environmental conditions, as well as their potentially differential associations across developmental domains [10].

4.4. Clinical implications

The findings of the present study underscore the importance of considering parental psychopathological symptoms in both parents during the NICU stay, including not only traditional indicators such as anxiety and depression, but also other specific dimensions of parental psychological adjustment identified in this study, such as partner phobic anxiety, maternal interpersonal sensitivity, and maternal paranoid ideation. In addition, the association between maternal postnatal bonding difficulties and neurodevelopmental outcomes highlights the relevance of NICU-based interventions that promote parent-infant bonding. Finally, neonatal and contextual factors such as infant male sex, length of NICU stay, 5-min Apgar score, and maternal foreign origin may help inform clinical follow-up and facilitate the early identification of potential neurodevelopmental difficulties.

However, given the observational and exploratory nature of the study, these clinical implications should be interpreted cautiously and should be considered as a basis for further research rather than as definitive recommendations for clinical practice.

5. Strengths, limitations, and future directions

Among the main strengths of the study are its longitudinal design and the joint consideration of biomedical and psychosocial factors in an integrative analysis of neurodevelopmental trajectories. In addition, the study included the assessment of postnatal bonding and parental mental health in both parents, incorporating specific dimensions of psychological adjustment beyond anxiety and depression. Moreover, the study incorporated multiple sources of information, including neonatal clinical indicators, parental self-report measures, and standardized neurodevelopmental assessments.

However, several limitations should be considered when interpreting the findings. First, the assessment of parental mental health and postnatal bonding was based on self-report measures, which may introduce response bias. Second, the generalizability of the findings may be limited by the single-center recruitment, the relative homogeneity of the sample, the requirement of Spanish proficiency as an inclusion criterion, and the limited representation of diverse family structures. Third, model-specific complete-case analyses for baseline predictors and incomplete follow-up data may have introduced some degree of bias, particularly given the higher proportion of mothers of foreign origin among infants with incomplete follow-up. Fourth, given the sample size and exploratory modelling approach, some associations may be sensitive to sampling variability and should be interpreted as hypothesis-generating. In addition, although the study included several neonatal indicators, more detailed neonatal morbidity variables and individual ultrasound- or MRI-based markers of early structural brain vulnerability were not available, which may have contributed to residual confounding. Finally, the study was conducted partially during the COVID-19 pandemic, an exceptional context that may have influenced parental psychological symptoms and neurodevelopmental follow-up assessments. A further methodological consideration is the transition from corrected age at 12 and 24 months to chronological age at 36 months, which should be considered when interpreting developmental change.

Future research should include larger, more diverse, and multicenter samples to improve the generalizability and stability of the findings. Future studies should also incorporate more specific neonatal clinical indicators and neuroimaging markers. Finally, replication is needed to confirm these findings and to better understand the mechanisms underlying the observed associations through the formal examination of potential mediating and moderating variables.

6. Conclusion

The present study indicates that neurodevelopment in VPT/VLBW infants during the first three years of life is associated with both biomedical and psychosocial factors in the early environment. The findings highlight the potential relevance of psychosocial factors, particularly parental mental health and postnatal bonding, in cognitive and language domains, whereas biomedical factors were mainly associated with motor development. The observed domain-specificity suggests that different types of predictors do not contribute uniformly to child neurodevelopment, reinforcing the need to adopt an integrative and multidimensional approach to early assessment and support in this population.

CRediT authorship contribution statement

Anna Riera-Martín: Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Data curation, Conceptualization. **Ana Calvo:** Writing – review & editing, Supervision, Conceptualization. **María Estévez-Domingo:** Writing – review & editing, Resources, Investigation. **Lore Zumeta-Olaskoaga:** Writing – review & editing, Visualization, Validation, Software, Methodology, Formal analysis. **Eduardo Fernández-Jiménez:** Writing – review & editing, Supervision. **Álvaro Iruin Sanz:** Writing – review & editing, Resources, Project administration, Funding acquisition, Data curation. **Anna Torres-Giménez:** Writing – review & editing, Supervision. **Miguel Moreno-Íñiguez:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.earlhumdev.2026.106620.

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