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Effects of maternal sensitivity on low birth weight children's academic achievement: a test of differential susceptibility versus diathesis stress

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Background: Differential Susceptibility Theory (DST) postulates that some children are more affected – for better and for worse – by developmental experiences, including parenting, than others. Low birth weight (LBW, 1,500–2,499 g) may not only be a predictor for neurodevelopmental impairment but also a marker for prenatally programmed susceptibility. The aim was to test if effects of sensitive parenting on LBW and very LBW (VLBW, <1,500 g) versus normal birth weight (NBW, ≥2,500 g) children's academic achievement are best explained by a differential susceptibility versus diathesis-stress model of person-X-environment interaction. **Methods:** Nine hundred and twenty-two children ranging from 600 g to 5,140 g birth weight were studied as part of a prospective, geographically defined, longitudinal investigation of neonatal at-risk children in South Germany (Bavarian Longitudinal Study). Sensitive parenting during a structured mother–child interaction task was observed and rated at age 6 years. Academic achievement was assessed with standardized mathematic, reading, and spelling/writing tests at age 8 years. **Results:** Maternal sensitivity positively predicted the academic achievement of both LBW (n = 283) and VLBW (n = 202) children. Confirmatory-comparative and model-fitting analysis (testing LBW vs. NBW and VLBW vs. NBW) indicated that LBW and VLBW children were more susceptible than NBW to the adverse effects of low-sensitive, but not beneficial effects of high-sensitive parenting. **Conclusions:** Findings proved more consistent with the diathesis stress than differential-susceptibility model of person-X-environment interaction: LBW and VLBW children's exposure to positive parenting predicted catch-up to their NBW peers, whereas exposure to negative parenting predicted much poorer functioning. **Keywords:** Differential susceptibility, diathesis stress, low birth weight, academic achievement, maternal sensitivity.

Introduction

Most research on the long-term effects of low birth weight (LBW, 1,500–2,499 g) on child development is informed by a deficit perspective. Well appreciated, however, is that sensitive parenting may protect children from developmental risk, enabling them to function like those born with normal birth weight (NBW, >2,500 g) (Orton, Spittle, Doyle, Anderson, & Boyd, 2009; Wolke, Jaekel, Hall, & Baumann, 2013). Differential Susceptibility Theory (DST) posits that children who would be considered more vulnerable to contextual risk within a traditional diathesis-stress framework (Zuckerman, 1999), like LBW children, may actually be more susceptible to environmental influences such as parenting—in a *for-better-and-for-worse* fashion (Belsky & Pluess, 2009). Thus, more susceptible children may not only be more negatively affected by contextual adversity but also benefit disproportionately from environmental support and enrichment. From this perspective, what might be traditionally seen as a risk factor may, within an evolutionary framework (Belsky & Pluess, 2009; Ellis & Boyce, 2011), be regarded as a susceptibility factor (Belsky, Bakermans-Kranenburg, & van IJzendoorn, 2007). The question we address here is whether LBW status, typically regarded as a risk factor, may make LBW children more susceptible than NBW children not just to the adverse effects of insensitive parenting, but also to the beneficial effects of sensitive parenting.

There is reason to suspect that LBW infants may prove particularly susceptible to developmental experiences and environmental exposures. Perhaps most notably, they often show increased negative emotionality (Meier, Wolke, Gutbrod, & Rust, 2003) and such negativity early in life, including when prenatally 'programmed', has been found to operate as a plasticity factor (Pluess & Belsky, 2011), making children more susceptible 'for better and for worse'. Thus, while it is well established that LBW slightly increases the risk of adverse outcomes, it may also make children more susceptible to positive environmental inputs. Although a number of previous studies indicate that LBW children may indeed be highly susceptible to parenting effects, samples have often been small (van der Kooy-Hofland, van der Kooy, Bus, van Ijzendoorn, & Bonsel, 2012; Shah, Robbins, Coelho, & Poehlmann, 2013) and the

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possibility of DST effects has not been formally investigated (Blair, 2002; Erickson et al., 2013). It thus remains unclear whether DST or diathesis-stress models of environmental action best capture LBW children's developmental response to variation in rearing experiences. This is not only an important theoretical issue but a translational one as well, due to the fact that better understanding of 'what works for whom' is essential to enhancing the efficacy of intervention efforts (Belsky & van Ijzendoorn, 2014), including the case of at-risk populations such as LBW children (Belsky, Pluess, & Widaman, 2013; Orton et al., 2009).

In contrast to LBW, survival of very LBW (VLBW, <1,500 g) infants has only become possible over the last half century due to advances in intensive neonatal care (Ruegger, Hegglin, Adams, Bucher, & Swiss Neonatal, 2012). VLBW children experience high neonatal risk and complications that have been associated with changes in the central nervous system (Bäuml et al., 2014; Jaekel, Wolke, & Bartmann, 2013; Volpe, 2009). Such neurological changes may increase their sensitivity to negative effects of contextual adversity while also limiting their potential to benefit from supportive environments (Obradović, 2012). Relatedly, a large intervention study found that children born at 2,001–2,499 g birth weight (BW) profited from preschool education programs, whereas those with BW ≤2,000 g derived no significant benefit from such exposure (McCormick et al., 2006).

Hence, it seems reasonable that VLBW children, who would never have survived over the course of evolutionary history, would prove disproportionately vulnerable to the adverse effects of low-sensitive parenting, without benefiting disproportionately from high-sensitive parenting. LBW children on the other hand, who would have been more likely to survive over the course of evolutionary history, would prove especially susceptible to both sensitive and insensitive parenting, due perhaps to the prenatal programming of postnatal plasticity (Pluess & Belsky, 2011). Thus, we test the proposition that both LBW and VLBW children will underperform NBW children when subject to insensitive parenting, but only LBW children will outperform them when sensitive care is experienced. Toward this end, we employ a newly developed competitive model-fitting approach that directly contrasts diathesis-stress and differential-susceptibility models of person-X-environment interaction.

Methods

Participants

Data were collected as part of the prospective Bavarian Longitudinal Study (BLS) (Wolke & Meyer, 1999). The BLS is a geographically defined whole-population sample of neonatal at-risk children born in Southern Bavaria (Germany) between January 1985 and March 1986 who required admission to a children's hospital within the first 10 days of life (N = 7,505; 10.6% of all live births). Additionally, 916 healthy control infants (normal postnatal care) were identified at birth from the same hospitals in Bavaria during the same period. Of the initial sample, n = 676 children born between 25 and 38 weeks of gestation (randomly drawn within the stratification factors gender, socioeconomic background and degree of neonatal risk) and n = 246 healthy full-term (39–41 weeks gestational age) control children were assessed at 6 and 8 years of age. Full details of the sampling criteria and dropout rates are provided elsewhere (Wolke & Meyer, 1999). Table 1 shows the characteristics of the final sample according to their NBW, LBW, and VLBW group status (N = 922).

Procedure

Participating parents were approached within 48 hours of the infant's hospital admission and were included in the study once they had given written consent for their child to participate. Parenting was assessed at age 6 and child functioning at age 8. All raters were blind to group membership. Ethical permission for the study was granted by the Ethics committee of the University of Munich Children's

Table 1 Descriptive characteristics of the study participants according to birth weight group status (N = 922)

Birth weight groups	<1,500 g n = 202	1,500–2,499 g n = 283	≥2,500 g n = 437	F/χ^2, p
Birth weight (g)	1,178 (215)	1,989 (298)	3,261 (466)	2,411.38, <.001
Gestational age (weeks)	30.58 (2.59)	33.83 (2.47)	38.63 (1.81)	1,024.88, <.001
Small for gestational age (SGA) births	57.1%	33.8%	8.0%	182.69, <.001
Multiple births	23.3%	13.4%	2.5%	67.75, <.001
Child sex (male)	43.8%	55.6%	50.7%	6.59, .037
Family SES (1 = low, 6 = high)	3.39 (1.48)	3.72 (1.59)	3.59 (1.56)	2.71, .067
Neurodevelopmental impairment at 6 years	34.2%	8.1%	13.7%	62.59, <.001
Maternal sensitivity at 6 years	−0.14 (0.73)	0.04 (0.70)	0.10 (0.62)	8.81, <.001
Mathematic Test Score[a] at 8 years	−0.63 (0.79)	−0.12 (0.71)	0.01 (0.68)	55.98, <.001
Reading Test Score[a] at 8 years	−0.78 (2.02)	−0.03 (1.19)	0.03 (0.88)	28.87, <.001
Spelling/Writing Test Score[a] at 8 years	−0.61 (1.18)	−0.05 (1.07)	−0.04 (1.07)	21.90, <.001

Data are presented as M (SD) for interval scaled and *percentages* for categorical variables.
[a]Dependent variables were z-standardized according to healthy full-term control children's scores (n = 246).

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Measures

Sensitive parenting behavior. Before children began elementary school, with 94% in kindergarten, mother–child interaction was observed during a standardized dyadic play situation which simulated a homework task. Mother and child used an Etch-a-Sketch to copy a template; this toy allows one to draw pictures by means of two control knobs, one that draws horizontal and the other vertical lines. The instruction was that the mother should use one control and the child the other, thus requiring mother and child to work together. If after 12 min there was no complete picture the session was terminated. Mother and child behavior was rated in vivo by experienced psychologists using a standardized coding system, the 'Assessment of Mother-Child-Interaction with the Etch-a-Sketch (AMCIES)' (Jaekel, Wolke, & Chernova, 2012). All raters received intensive training, with bimonthly feedback and refresher sessions. Rating scales consisted of three subscales for the mother (Verbal Control, Non-Verbal Control, and Criticism, all reverse-coded) and one subscale for mother–child joint behavior (Harmony) (Wolke et al., 2013). These were used to create a single index of Maternal Sensitivity by averaging the component scores (Cronbach's $\alpha = .581$). The AMCIES coding system has established high inter-rater reliabilities (Jaekel et al., 2012). For a subsample ($n = 565$), the in vivo rated scores used for the current study could be compared with video-rated scores of Maternal Sensitivity (Wolke et al., 2013) and showed excellent convergence (intraclass-correlation coefficient of .76, $p < .001$, for two master raters).

Neurodevelopmental impairment. At age 6 years, an Index of Neurodevelopmental Impairment was generated (coded binary 0 vs. 1; any impairment = 1). Children were coded as 1 if they had one or more of the following problems: severe cerebral palsy [CP grade 3 or 4 (Hagberg, Hagberg, Olow, & Wendt, 1989)], hearing loss (not corrected), blindness, IQ [K-ABC MPC Score (Melchers & Preuss, 1991)] <-2 *SD* below the mean (Wolke & Meyer, 1999), any DSM-IV diagnosis of internalizing or externalizing disorders (including ADHD, depression, anxiety, eating disorders, and peer behavior disorder).

School achievement: Mathematic, reading, and spelling/writing abilities. School achievement was assessed with standardized tests. Numerical representations and reasoning were measured with a comprehensive mathematic test (Jaekel & Wolke, 2014; Wolke & Leon-Villagra, 1993). Test tasks were presented to children in book form with 79 items assessing numerical estimations, calculation, reasoning, and mental rotation abilities. Item responses were scored for accuracy and subscale scores were then summed into a total Mathematic Test Score. Children's reading abilities were measured with the Zürich Reading Test (Grissemann, 2000) and a pseudoword reading test (Leon-Villagra & Wolke, 1993; Schneider, Wolke, Schlagmüller, & Meyer, 2004). Total scores (based on number of errors) correlated highly with each other ($r = .74$, $p < .001$) and were thus combined to create a single, composite Reading Test Score. Spelling and writing were assessed with a standard diagnostic test (DRT 2) (Müller, 1983). Test scores were z-standardized according to healthy full-term control children's scores ($n = 246$).

Analytic approach

Applying recently developed methodology to competitively evaluate DST versus diathesis-stress interaction patterns (Belsky et al., 2013; Widaman et al., 2012) we investigated whether LBW and VLBW may function as plasticity or risk factors. Analyses were conducted using IBM SPSS Version 22 (SPSS Inc, Chicago, IL, USA). All reported tests are two-tailed with $\alpha = .05$. For each outcome (i.e., maths, reading, spelling/writing) and each group comparison (i.e., LBW vs. NBW and VLBW vs. NBW), we first, used exploratory regression models to delineate the main effects of BW group and maternal sensitivity (Model 1) as well as the interaction effect of BW X sensitivity (Model 2). We then performed confirmatory testing by fitting four different reparameterized regression models to the data. This method systematically varies the number of parameters included in the regression equations in order to evaluate alternative models of weak and strong DST versus diathesis stress (Belsky et al., 2013). Consistent with DST, the respective models (3a and 3b) predict that regression lines cross within the range of values of the measured environment (i.e., sensitivity), whereas the more parsimonious diathesis-stress models presume that regression lines cross at or above the most positive observed value of sensitivity (Models 3c and 3d). The strong version of each model predicts that NBW children are not affected at all by maternal sensitivity (Models 3a and 3c), whereas the weak differential susceptibility (Model 3b) and weak diathesis-stress (Model 3d) versions suggest that NBW children are also affected by sensitivity, but to a lesser degree than LBW or VLBW children. Finally, proportions of variance explained by each model were compared in order to determine which model provided the best fit to the data.

Results

According to preliminary analyses, mean values of maternal sensitivity and academic achievement test scores were lower among VLBW compared with both

LBW and NBW children, whereas there were no significant differences between LBW and NBW children's scores (see Table 1). Univariate regressions *within* BW groups showed that maternal sensitivity was positively and significantly associated with academic achievement across all domains (maths, reading, spelling/writing) in both LBW and VLBW children, but only with maths test scores in NBW children. Fisher's *Z*-Tests revealed that the sensitivity regression weights on reading were significantly steeper in both LBW ($Z = 3.11$, $p = .002$) and VLBW ($Z = 5.39$, $p < .001$) than NBW children. No group differences emerged for maths and spelling/writing abilities and parenting-achievement associations were not different across LBW and VLBW children.

LBW versus NBW children

Standard exploratory analysis. Table 2 shows that, first, Model 1 which included a categorical BW group variable and maternal sensitivity as predictors was fit to LBW and NBW children's academic achievement data. It yielded R^2 values of .06/.01./.01 for, respectively, maths/reading/spelling-writing. The main effect of BW group was significant only for maths ($B_2 = .12$ ($SE = .05$), $p = .03$), but that of maternal sensitivity proved significant for all outcomes. Thus, higher birth weight predicted better maths performance and greater sensitivity forecast better performance across the board. Adding the BW-x-sensitivity interaction to the prediction (Model 2) significantly increased R^2 (ΔR^2) only in the case of reading ($B_3 = -.25$ ($SE = .12$), $p = .04$).

Differential susceptibility versus diathesis-stress competitive model fitting. As described in detail before (Belsky et al., 2013), we next fitted four different reparameterized versions of Model 2 in order to compare the fit of both strong and weak DST (Models 3a and 3b, respectively) and diathesis-stress models (Models 3c and 3d, respectively) in LBW versus NBW children. The model fit values in Table 2 indicate that Model 3d, the weak diathesis-stress model, provided the best fit to the data for all three achievement outcomes. Model 3b, the weak DST model, fit the data almost as well, but the amount of variance explained was not significantly different from the more parsimonious weak diathesis-stress model 3d. Thus, although visual inspection of the effects of maternal sensitivity on LBW children's achievement appeared consistent with DST (Figure 1) and all of the estimated cross-over points (C) and their 95% confidence intervals (CI) for the weak DST model (except the upper CI limit for maths) were within the observed range of sensitivity (-1.95 to 1.41), comparative analysis indicated that the relationship between maternal sensitivity and academic outcomes in LBW children was more supportive of vulnerability to the adverse effects of low sensitivity compared to NBW children.

VLBW versus NBW children

Standard exploratory analysis. Table 3 shows that, as for LBW and NBW children, Model 1 was first fit to VLBW and NBW children's academic achievement data, yielding R^2 values of .23/.11/.10 for, respectively, maths/reading/spelling-writing, with both main effects of BW group and maternal sensitivity significantly predicting achievement in all models. Thus, higher birth weight and greater maternal sensitivity each predicted better achievement across the board. Adding the BW-x-sensitivity interaction to the prediction equation (Model 2) significantly increased R^2 (ΔR^2) only in the case of reading ($B_3 = -.52$ ($SE = .17$), $p < .01$).

Differential susceptibility versus diathesis-stress competitive model fitting. Statistical comparison of the reparameterized Models 3a–3d in VLBW versus NBW children, displayed in Table 3, showed that, again, Model 3d, the weak diathesis-stress model, provided the best fit to the data for reading and spelling/writing abilities while Model 1 had the best for maths. In addition, and consistent with these findings, most of the estimated cross-over points and their 95% CIs for the VLBW versus NBW DST models were far outside the range of the sensitivity measure (-1.93 to 1.67) as inspection of Figure 1 suggests. Consequently, while VLBW children proved more vulnerable to low levels of maternal sensitivity compared with NBW children, they did not disproportionately benefit from high levels.

Subgroup analyses on children without any neurodevelopmental impairment

To investigate whether differential susceptibility rather than diathesis stress might characterize the development of LBW or VLBW children free of neurological impairment by 6 years of age (please see Table 1 for descriptive information), we repeated our analyses [Models 1–3d, comparing LBW vs. NBW ($n = 637$) and VLBW versus NBW ($n = 510$)] on this subgroup. Results were essentially unchanged, with the weak diathesis-stress model once more fitting the data best, except in the case of reading, where the strong diathesis-stress model best fit the VLBW versus NBW group comparison.

Discussion

Both LBW and VLBW children appeared more affected – in a diathesis-stress manner – by sensitive parenting experiences than NBW children in this observational study. LBW, just like VLBW children, showed compensatory academic performance in maths, reading, and spelling/writing at age 8 years

Table 2 Results of alternate regression models for LBW versus NBW children's mathematic, reading, and spelling/writing abilities at 8 years (N = 720)

	Standard parameterization		Reparameterized regression equations				
				Differential susceptibility		Diathesis Stress	
Parameter	Model 1	Model 2	Parameter	Strong: Model 3a	Weak: Model 3b	Strong: Model 3c	Weak: Model 3d
Mathematic abilities							
B_0 *(intercept)*	**–.13 (.04)**	**–.14 (.04)**	B_0	**–.12 (.04)**	.22 (.24)	.04 (.00)	**.28 (.00)**
B_1 *(sensitivity)*	**.25 (.04)**	**.30 (.06)**	B_1	.00 (–)[a]	**.30 (.06)**	.00 (–)[a]	**.30 (.04)**
B_2 *(BW group)*	**.12 (.05)**	**.12 (.05)**	**C**	–.55 (.32)	1.18 (.97)	1.41 (–)[a]	1.41 (–)[a]
B_3 *(interaction)*	–	–.11 (.08)	B_3	**.20 (.06)**	**.20 (.05)**	.00 (.04)	**.21 (.06)**
R^2	.063	.066	R^2	.030	.066	.004	.066
***F* vs. 1**	–	1.74	***F* vs. 3b**	27.343	–	23.794	0.042
df	–	1, 716	***df***	1, 716	–	2, 716	1, 716
p	–	0.188	***p***	<.001	–	<.001	.837
	–	–	***F* vs. 3c**	19.531	23.796	–	47.613
	–	–	***df***	1, 717	2, 716	–	1, 717
	–	–	***p***	<.001	<.001	–	<.001
AIC	–572.450	–572.194	**AIC**	–547.210	–572.194	–529.859	–574.151
BIC	–570.424	–570.149	**BIC**	–545.185	–570.149	–527.848	–572.126
Reading abilities							
B_0 *(intercept)*	–.03 (.06)	–.04 (.06)	B_0	–.03 (.00)	.04 (.06)	–.00 (.00)	**.20 (.00)**
B_1 *(sensitivity)*	**.16 (.06)**	**.29 (.09)**	B_1	.00 (–)[a]	**.29 (.09)**	.00 (–)[a]	**.19 (.07)**
B_2 *(BW group)*	.05 (.08)	.06 (.08)	**C**	–1.22 (3.21)	.26 (.33)	1.41 (–)[a]	1.41 (–)[a]
B_3 *(interaction)*	–	**–.25 (.12)**	B_3	.04 (.06)	.04 (.08)	–.01 (.05)	.12 (.09)
R^2	.010	.016	R^2	.001	.016	.000	.012
***F* vs. 1**	–	4.204	***F* vs. 3b**	10.780	–	5.748	2.531
df	–	1, 716	***df***	1, 716	–	2, 716	1, 716
p	–	.041	***p***	.001	–	.003	.112
	–	–	***F* vs. 3c**	0.706	5.748	–	8.946
	–	–	***df***	1, 717	2, 716	–	1, 717
	–	–	***p***	.401	.003	–	.003
AIC	22.644	20.429	**AIC**	29.189	20.429	27.897	20.969
BIC	24.669	22.474	**BIC**	31.214	22.474	29.908	22.994
Spelling/writing abilities							
B_0 *(intercept)*	–.05 (.06)	–.06 (.06)	B_0	–.05 (.06)	–.04 (.08)	–.02 (.00)	.17 (.00)
B_1 *(sensitivity)*	**.16 (.06)**	**.25 (.09)**	B_1	.00 (–)[a]	**.25 (.09)**	.00 (–)[a]	**.18 (.07)**
B_2 *(BW group)*	.00 (.08)	.01 (.08)	**C**	–.03 (.92)	.09 (.49)	1.41 (–)[a]	1.41 (–)[a]
B_3 *(interaction)*	–	–.16 (.12)	B_3	.09 (.08)	.09 (.08)	.02 (.06)	**.15 (.09)**
R^2	.011	.014	R^2	.003	.014	.002	.012
***F* vs. 1**	–	1.745	***F* vs. 3b**	7.749	–	4.320	1.396
df	–	1, 716	***df***	1, 716	–	2, 716	1, 716
p	–	.187	***p***	.006	–	.014	.238
	–	–	***F* vs. 3c**	0.883	4.320	–	7.241
	–	–	***df***	1, 717	2, 716	–	1, 717
	–	–	***p***	.348	.014	–	.007
AIC	46.894	47.142	**AIC**	52.892	47.142	51.778	46.544
BIC	48.919	49.186	**BIC**	54.917	49.186	53.789	48.569

AIC, Akaike information criterion; BIC, Bayesian information criterion. Tabled values are parameter estimates with their standard errors in parentheses. Significant parameter estimates are marked bold. F versus 1 stands for an F test of the difference in R^2 for Model 2 versus Model 1. F versus 3b stands for an F test of the difference in R^2 for a given Model versus Model 3b. F versus 3c stands for an F test of the difference in R^2 for a given Model versus Model 3c.
[a]Parameter fixed at reported value; *SE* not applicable.

compared with NBW children under conditions of highly sensitive parenting (i.e., performing as well as NBW children), yet both underperformed their NBW peers when exposed to low-sensitive mothering.

According to the fetal programming hypothesis (Barker, 1998), children's birth weight may reflect their prenatal environment and serve as a cue of the postnatal world that the developing fetus is likely to encounter following birth (Raikkonen & Pesonen, 2009). Recently, it has been suggested that prenatal adversity signals the developing fetus that the postnatal environment may be unpredictable and require flexible adaptation to changes (Pluess & Belsky, 2011). Hence, prenatal adversity may program a higher degree of postnatal developmental plasticity while also being associated with lower birth weight as a function of fetal growth retardation (Raisanen, Gissler, Saari, Kramer, & Heinonen, 2013). As a consequence, LBW and VLBW children may be equipped with enhanced capacity for developmental plasticity to facilitate such adaptation to uncertain

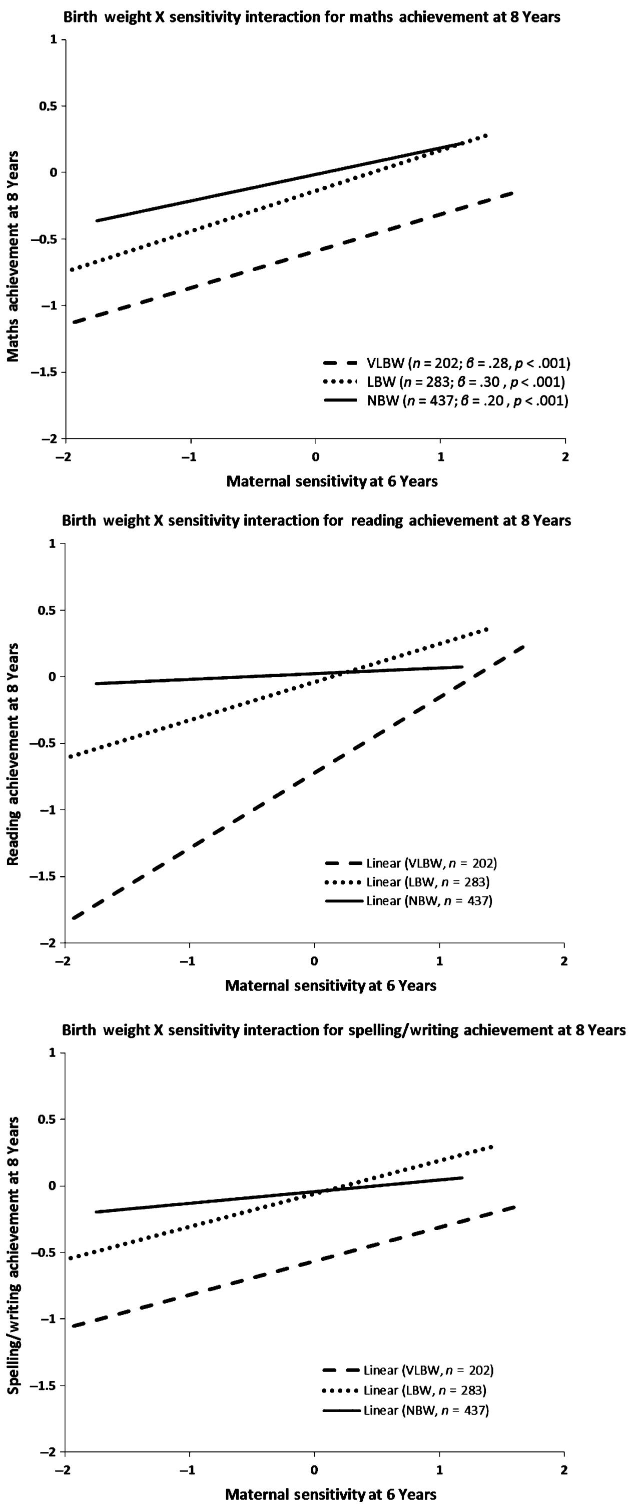

Figure 1 Birth weight X sensitivity interactions for maths, reading, and spelling/writing test scores (N = 922)

postnatal environments. Thus, we asked whether such enhanced plasticity is evident in one or both low birth-weight groups and, if so, whether it reflects heightened responsiveness to both adverse and supportive postnatal environments. Recall that evolutionary considerations – that is, which of these infants would most likely have survived over the course of human history – led us to predict that LBW children would prove especially susceptible 'for better and for worse', but VLBW children only 'for worse'.

Our confirmatory model testing revealed that both LBW and VLBW children's developmental response to variation in rearing experience was most consistent with a diathesis-stress model of environmental action – elevated susceptibility only 'for worse' – even though there was a cross-over interaction between VLBW and NBW regarding reading and spelling/writing. One reason the diathesis-stress model may have prevailed is that both LBW and VLBW infants are often born premature with an increased risk for neurological deficits (de Kieviet, Zoetebier, van Elburg, Vermeulen, & Oosterlaan, 2012). As a result, they may lack the neurobiological resources to take advantage of especially supportive care (i.e., altered brain organization to reach higher performance, (Bäuml et al., 2014), at least in terms of excelling relative to NBW children. Although appealing, this post hoc account of our differential predictions for LBW and VLBW children also had to be rejected, recall that it could not be substantiated in our secondary analysis on a subgroup of children who were free of any neurodevelopmental impairment. Thus, even when we focused on only LBW and VLBW children who had no disabilities at age 6, the diathesis-stress model still fit the data best. Differential-susceptibility was still trumped by diathesis-stress. Both LBW and VLBW, then, prove more vulnerable to poor environmental conditions, while appearing to require high-sensitive parenting to achieve at the same level as their NBW peers. Healthy NBW children, on the other hand, emerge as relatively hypo-susceptible to parenting experiences although they also profit from maternal sensitivity (Jaekel et al., 2012; Wolke et al., 2013).

Maternal sensitivity promotes maturation and connectivity of cerebral white matter in premature infants (Milgrom et al., 2010). While parenting interventions may not have long-term positive effects on the cognitive/academic functioning of VLBW children (McCormick et al., 2006; Orton et al., 2009b), McCormick et al. reported long-term benefits of preschool education programs in LBW children born at 2,001–2,499 g BW (McCormick et al., 2006). The conceptualization of two competing forces of increased susceptibility (i.e., developmental plasticity) versus limited potential for functional adaptation following neurological reorganization may help explain these findings. LBW children may have potential for high performance, at least as indicated by visual inspection of our data which seemed consistent with DST. We have previously shown with an observational study that parents could provide particular academic support for their VLBW children with highly sensitive parenting before school entry (Wolke et al., 2013). Thus, an intervention aimed at fostering maternal sensitivity may *prevent* LBW and VLBW children's *under*achievement, and there is evidence that sensitive parenting can be facilitated

Table 3 Results for alternate regression models for VLBW versus NBW children's mathematic, reading, and spelling/writing abilities at 8 years (N = 639)

	Standard parameterization		Reparameterized regression equations				
				Differential susceptibility		Diathesis Stress	
Parameter	Model 1	Model 2	Parameter	Strong: Model 3a	Weak: Model 3b	Strong: Model 3c	Weak: Model 3d
Mathematic abilities							
B_0 *(intercept)*	**–.60 (.05)**	**–.59 (.05)**	**B_0**	**–.62 (.00)**	1.47 (2.04)	**–.42 (.00)**	**.18 (.00)**
B_1 *(sensitivity)*	**.23 (.04)**	**.28 (.07)**	**B_1**	.00 (–)[a]	**.28 (.07)**	.00 (–)[a]	**.42 (.05)**
B_2 *(BW group)*	**.58 (.06)**	**.58 (.06)**	**C**	**–3.07 (.97)**	7.47 (8.82)	1.67 (–)[a]	1.67 (–)[a]
B_3 *(interaction)*	–	–.08 (.09)	**B_3**	**.20 (.05)**	**.20 (.06)**	**–.22 (.05)**	**.12 (.08)**
R^2	.227	.228	**R^2**	.209	.228	.113	.219
***F* vs. 1**	–	0.730	***F* vs. 3b**	15.269	–	47.106	7.343
df	–	1, 635	***df***	1, 635	–	2, 635	1, 635
p	–	.393	***p***	<.001	–	<.001	.007
	–	–	***F* vs. 3c**	77.211	47.106	–	86.012
	–	–	***df***	1, 636	2, 635	–	1, 636
	–	–	***p***	<.001	<.001	–	<.001
AIC	–452.403	–451.137	**AIC**	–437.954	–451.137	–366.738	–445.790
BIC	–450.375	–449.087	**BIC**	–435.926	–449.087	–364.726	–443.762
Reading abilities							
B_0 *(intercept)*	**–.76 (.10)**	**–.72 (.10)**	**B_0**	**–.79 (.00)**	.08 (.17)	**–.60 (.00)**	.14 (.00)
B_1 *(sensitivity)*	**.25 (.09)**	**.56 (.14)**	**B_1**	.00 (–)[a]	**.56 (.14)**	.00 (–)[a]	**.52 (.09)**
B_2 *(BW group)*	**.76 (.12)**	**.74 (.12)**	**C**	–19.33 (50.62)	**1.42 (.53)**	1.67 (–)[a]	1.67 (–)[a]
B_3 *(interaction)*	–	**–.52 (.17)**	**B_3**	.04 (.10)	.04 (.11)	**–.35 (.09)**	.07 (.15)
R^2	.109	.122	**R^2**	.098	.122	.072	.122
***F* vs. 1**	–	9.169	***F* vs. 3b**	17.557	–	18.204	0.168
df	–	1, 635	***df***	1, 635	–	2, 635	1, 635
p	–	.003	***p***	<.001	–	<.001	.682
	–	–	***F* vs. 3c**	18.372	18.204	–	36.287
	–	–	***df***	1, 636	2, 635	–	1, 636
	–	–	***p***	<.001	<.001	–	<.001
AIC	380.726	373.565	**AIC**	388.993	373.565	405.190	371.734
BIC	382.754	375.616	**BIC**	391.021	375.616	407.203	373.763
Spelling/writing abilities							
B_0 *(intercept)*	**–.58 (.08)**	**–.57 (.08)**	**B_0**	**–.60 (.00)**	.23 (.45)	**–.45 (.00)**	.02 (.00)
B_1 *(sensitivity)*	**.15 (.07)**	**.25 (.10)**	**B_1**	.00 (–)[a]	**.25 (.11)**	.00 (–)[a]	**.33 (.07)**
B_2 *(BW group)*	**.53 (.09)**	**.52 (.09)**	**C**	–6.35 (6.47)	3.17 (2.72)	1.67 (–)[a]	1.67 (–)[a]
B_3 *(interaction)*	–	–.17 (.14)	**B_3**	.09 (.08)	.09 (.09)	**–.22 (.07)**	.04 (.12)
R^2	.098	.100	**R^2**	.092	.100	.066	.099
***F* vs. 1**	–	1.444	***F* vs. 3b**	5.538	–	12.233	0.979
df	–	1, 635	***df***	1, 635	–	2, 635	1, 635
p	–	.230	***p***	.019	–	<.001	.323
	–	–	***F* vs. 3c**	18.794	12.233	–	23.487
	–	–	***df***	1, 636	2, 635	–	1, 636
	–	–	***p***	<.001	<.001	–	<.001
AIC	79.455	80.004	**AIC**	83.552	80.004	100.161	78.988
BIC	81.483	82.054	**BIC**	85.580	82.054	102.173	81.017

AIC, Akaike information criterion; BIC, Bayesian information criterion. Tabled values are parameter estimates with standard errors in parentheses. Significant parameter estimates are marked bold. F versus 1 stands for an F test of the difference in R^2 for Model 2 versus Model 1. F versus 3b stands for an F test of the difference in R^2 for a given Model versus Model 3b. F versus 3c stands for an F test of the difference in R^2 for a given Model versus Model 3c.
[a]Parameter fixed at reported value; *SE* not applicable.

by training (Bakermans-Kranenburg, van Ijzendoorn, & Juffer, 2003; van den Boom, 1997; Milgrom et al., 2010). But again the current study provides no evidence that such intervention enables LBW or VLBW children to outperform their NBW peers, as differential susceptibility thinking might lead one to expect.

Strengths and limitations

This is the first study to competitively evaluate alternative models of person-X-environment interaction (i.e., DST versus diathesis stress) in a large sample of neonatal at-risk children across the full BW range. Even though sensitive parenting was carefully and observationally measured, it was assessed post-infancy; effects detected here might have been different had parenting been measured in the first years of life. Given changes in neonatal and general medical care since the current cohort was recruited in the mid 1980s, there is also reason to wonder whether our results would generalize to neonatal at-risk children born today. In addition, we need to point out that we were unable to disentangle effects of birth weight and gestational age because they proved to be so highly correlated ($r = .88$, $p < .01$, $N = 922$). We did endeavor to take into account two important prenatal risk conditions, small for gestational age (SGA) and multiple birth status, that were more frequent the lower the birth weight. Because controlling for these factors negatively affected model fit and did not change the core results (i.e., the weak diathesis-stress model fitting the data best), no more consideration of them seemed appropriate.

Conclusion

Visual inspection and the cross-over points of our data suggested that LBW children may be highly susceptible to sensitive parenting – in the 'for-better-and-for-worse' manner central to differential susceptibility. Competitive model testing indicated, however, that the diathesis-stress framework fit the data best, sometimes due to the importance of parsimony in choosing between models. Thus, both LBW and VLBW children proved disproportionately susceptible – relative to NBW peers – to the negative effects of limited maternal sensitivity, while reaching comparable levels of achievement as NBW children when exposed to highly sensitive parenting. Contradicting our 'prenatal programming of postnatal plasticity hypothesis' (Pluess & Belsky, 2011), then, LBW status does not seem to increase children's capacity to disproportionately benefit from highly sensitive parenting.

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Key points

- LBW may not only be a predictor for neurodevelopmental impairment but also a marker for prenatally programmed and heightened susceptibility to positive as well as negative environmental exposures.
- LBW children are just as vulnerable to low levels of maternal sensitivity as VLBW children.
- Both LBW and VLBW achieve similar levels of academic achievement as NBW children if they experience highly sensitive parenting.
- A diathesis stress rather than differential-susceptibility model of person-X-environment interaction best characterizes LBW children's development.
- Research is needed to systematically test efficacy of parenting interventions aimed at increasing sensitivity for VLBW and LBW children at school age.

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