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Normal Birth Weight Variation and Children's Neuropsychological Functioning: Links between Language, Executive Functioning, and Theory of Mind

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Abstract

The effect of low birth weight on children's development has been documented for a range of neurocognitive outcomes. However, few previous studies have examined the effect of birth weight variability within the normal range on children's neuropsychological development. The current study examined birth weight variation amongst children weighing ≥ 2500 g in relation to their language, executive functioning (EF), and theory of mind (ToM), and specified a developmental pathway in which birth weight was hypothesized to be associated with children's EF and ToM through their intermediary language skills. The current study used a prospective community birth cohort of 468 children. Families were recruited when children were newborns and followed up every 18 months until children were age 4.5. Language was assessed at age 3 using a standardized measure of receptive vocabulary (PPVT), and EF and ToM were measured at age 4.5 using previously validated and developmentally appropriate tasks. After controlling for potential confounding variables (family income, parent education, gestational age), birth weight within the normal range was associated with language ability at age 3 ($\beta = .17$; $p = .012$); and the effect of birth weight on both EF ($z = 2.09$; $p = .03$) and ToM ($z = 2.07$; $p = .03$) at age 4.5 operated indirectly through their language ability at age 3. Our findings indicate that the effects of birth weight on child neurocognition extend into the normal range of birth weight, and specific developmental mechanisms may link these skills over time. (*JINS*, 2014, *20*, 909–919)

Keywords: Birth weight, Language, Executive functioning, Theory of mind, Neuropsychology, Neurocognition, Normal development

INTRODUCTION

Low birth weight (LBW; < 2500 g) is associated with a range of physical, cognitive, and neurobehavioral impairments in children and adolescents, including lower IQ (Anderson & Doyle, 2003), greater inattention and hyperactivity (Hack et al., 2009), poor motor development (de Kieviet, Piek, Aarnoudse-Moens, & Oosterlaan, 2009), lower academic achievement (Aarnoudse-Moens, Weisglas-Kuperus, van Goudoever, & Oosterlaan, 2009; Anderson & Doyle, 2003), impaired visual-spatial ability (Geldof, Van Wassenaer, de Kieviet, Kok, & Oosterlaan, 2011), and more internalizing and externalizing problems (Dahl et al., 2006; Grunau, Whitfield, & Fay, 2004). Among the most pronounced and robust deficits of LBW are problems with language and executive functioning (Aarnoudse-Moens et al., 2009). Executive functioning (EF) is the set of cognitive processes required for goal-directed action and problem-solving, including inhibition, working memory, shifting, and cognitive flexibility. However, little is currently known about the relationship between birth weight variability and neuropsychological outcomes for children weighing ≥ 2500 g (i.e., the normal range) despite the fact that the vast majority (92%) of the population falls within this range (Martin et al., 2009). The current study was designed to address this gap in the literature by testing a developmental mechanism, namely emergent language skills, linking normative birth weight variability to two critical neuropsychological capacities that unfold over the preschool period: executive functioning and theory of mind.

Impact of Relatively Low Birth Weight in Normative Samples

Within the LBW range, there is a dose-response relationship between birth weight and neurocognitive outcomes—higher

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birth weight is associated with better language, spatial ability, and attention (Breslau, Chilcoat, DelDotto, Andreski, & Brown, 1996). A similar pattern emerges for children born in the normal range. In a large study of 3484 children born within the normal range of birth weight, Matte, Bresnahan, Begg, and Susser (2001) showed that IQ at age 7 increased monotonically with birth weight. Other studies have since shown that normative variation in birth weight is related to academic abilities such as reading, arithmetic, and spelling at age 10 (Kirkegaard, Obel, Hedegaard, & Henriksen, 2006), and risk of developmental disabilities such as cerebral palsy, learning disabilities, and attention-deficit-hyperactivity disorder (ADHD) in 3- to 17-year-old children (Boulet, Schieve, & Boyle, 2011). Thus, the effect of birth weight on broad, complex phenotypes may be more far-reaching than previously thought.

Birth Weight Variability and Cognitive Domain-Specificity

One fundamental limitation of previous studies assessing the relation between birth weight and child outcomes is a lack of specificity in the neuropsychological domains that may be impacted by this perinatal factor. For instance, global measures of cognitive ability (e.g., Full-Scale IQ), phenomenological symptom clusters (e.g., psychiatric diagnoses), and phenotypically complex performance outcomes (e.g., academic achievement) offer little in the way of understanding the relatively discrete and modular cognitive processes that may be impacted by birth weight. Phua, Rifkin-Graboi, Saw, Meaney, and Qiu (2012) recently showed that higher birth weight within the normal range was associated with a linear increase in EF, suggesting that this may be one critical domain-specific neuropsychological capacity linking fetal growth to a range of developmental outcomes supported by EF. Consistent with this idea, Hatch, Healey, and Halperin (2014) showed that the effect of birth weight on ADHD symptom severity operated indirectly through children's EF. Aside from EF, however, little empirical attention has been devoted to the cognitive substrates related to birth weight differences within the normal range.

One cognitive skill that has yet to be examined in relation to birth weight differences is theory of mind (ToM)—the social-cognitive ability to interpret others' behavior in terms of underlying psychological states such as emotions, desires, intentions, and beliefs. There is reason to suspect that that this cognitive capacity may vary as a function of birth weight differences. For instance, there is a robust behavioral link between ToM and EF in the preschool period (Carlson, Moses, & Breton, 2002; Hughes, 1998), and children with ADHD also exhibit difficulties with social cognition (Uekermann et al., 2010). Recent neuroimaging evidence points to a potential neurological link between EF and ToM that involves the medial prefrontal cortex, temporo-parietal junction (TPJ), and lateral prefrontal areas (Gallagher & Frith, 2003; Rothmayr et al., 2011; Spreng, Mar, & Kim, 2009). Thus, it is conceivable that birth weight is associated with both EF and ToM owing to a shared neural network that is compromised in lower birth weight children (Walhovd et al., 2013).

Neural Correlates of Low Birth Weight

Studies examining the cortical regions affected by low birth weight show that LBW infants exhibit regional thinning of temporal and parietal regions (Martinussen et al., 2009), areas that have long been considered important for language production and understanding (Kennison, 2013). Damage to the TPJ has also been shown to instigate deficits in ToM (Apperly, Samson, Chiavarino, & Humphreys, 2004), and has been implicated in certain executive functions (Lie, Specht, Marshall, & Fink, 2006). Moreover, it has recently been suggested that the executive dysfunctions of LBW adolescents may be attributable to white matter abnormalities in the cingulum and fronto-occipital regions of prefrontal cortex (Skranes et al., 2009). Of interest, the cingulum connects the anterior cingulate cortex to the dorsolateral prefrontal cortex, and there is some evidence for the involvement of these areas in ToM-based tasks (Gallagher & Frith, 2003; Spreng et al., 2009; Stone, Baron-Cohen, & Knight, 1998). Thus, not only do ToM and EF share a common neural architecture when assessed in normative populations, but the brain regions damaged by low birth weight may be important for the development of both of these cognitive capacities. These results provide neurobiological evidence for the inter-connectedness of language, EF, and ToM, warranting the exploration of birth weight correlates for all three of these neuropsychological domains amongst children ≥ 2500 g.

Developmental Pathways of Neurocognitive Impairment

Another area that has been understudied is the developmental mechanism through which fetal risk relates to specific aspects of cognitive functioning. Language has long been considered a fundamental aspect of human cognition that augments the development of other cognitive faculties (Fernyhough, 2008; Vygotskiĭ, 1997). Empirical evidence shows that early language skills are predictive of later ToM (Astington & Jenkins, 1999) and EF (Hughes & Ensor, 2007a). Verbal mediation of EF and ToM is further suggested by studies showing that individuals with specific language impairment have broadband difficulties with many aspects of EF (Henry, Messer, & Nash, 2012) and ToM (Farrant, Fletcher, & Maybery, 2006). These findings are consistent with the notion that EF and ToM may rely on language due to the need for verbal self-reminding (Russell, Jarrold, & Hood, 1999), conscious reflection (Marcovitch & Zelazo, 2009), and the integration of domain-specific knowledge that enables the representation, reasoning, and strategic control of thought and action (Carruthers, 2002). No study to date has examined language as a mediating link between birth weight differences and other forms of cognition, either in low- or normal-birth weight samples. In the current study, we focused on receptive language, as this has been widely associated with children's ToM and EF in the preschool period (Fuhs & Day, 2011; Hughes & Ensor; 2005; Müller et al., 2012; Perner, Lang, & Kloo, 2002).

Goals of the Current Study

To date, drawbacks in the examination of birth weight disparities in child neurocognition include: (a) a paucity of research examining neuropsychological outcomes within the normal range of birth weight; (b) a lack of understanding about the specific neurocognitive domains impacted by low birth weight; (c) the exclusion of key neuropsychological abilities that are critical to children's psychosocial development, including theory of mind; and (d) little attention to the mechanisms through which birth weight differences contribute to neuropsychological functioning. The current study used a normative sample of 468 children to test the hypothesis that variability in birth weight ≥ 2500 g would be associated with children's EF and ToM ability at age 4.5, the latter of which has not previously been examined. Consistent with the mediating role of language in human cognition, it was further hypothesized that the relationship between birth weight and both EF and ToM would operate through children's intermediary language ability at 3 years.

METHOD

Participants

All women giving birth to infants in the cities of Toronto and Hamilton between February 2006 and February 2008 were considered for participation. Families were recruited through a program called *Healthy Babies Healthy Children*, run by the Public Health Units of Toronto and Hamilton, which contacts the parents of all newborn babies within 7 days of the child's birth. Inclusion criteria for the intensive sample of the Kids, Families, and Places study (iKFP) included: (1) an English-speaking mother; (2) a newborn > 1500 grams; (3) a sibling < 4 years old; and (4) agreement to be videotaped. Thirty-four percent of families approached agreed to take part. Reasons for non-enlistment included inability to contact families through the information given by public health, as well as refusals. The current study was embedded within a larger project, the goals of which were to examine genetic and environmental influences on children's socio-emotional development through the investigation of within-family differences. As we were interested in examining neurocognition as it was unfolding, the current study focuses exclusively on the newborn children enrolled in the study. The University of Toronto Research Ethics Board approved all procedures for this investigation, including informed consent.

At Time 1 (T1; infants were ~ 2 months old), 501 families were enlisted in the study. Due to sample attrition, 397 of the original 501 families were followed up at Time 2 (T2; children now ~ 18 months old), 385 were followed up at Time 3 (T3; ~ 3-years-old), and 323 were followed up at Time 4 (T4; children ~ 4.5-years-old). The current study drew on data from all time points to test the study hypotheses. Sample demographics at study entry are presented in Table 1.

On measures of demographics taken from the entire iKFP at study entry (T1; $N = 501$), the sample was representative of the general population of Toronto and Hamilton in terms of family size ($M = 4.52$; $SD = 1.01$ in iKFP compared to $M = 4.13$; $SD = 1.22$ in the Census data) and personal income ($30 000-39 999 compared to $30 504.16; SD = $37 808.12). However, the study sample had more educated mothers (53% had a Bachelor's degree *vs*. 30.6% in the general population), had fewer non-intact families (lone-parent: 5% *vs*. 16.8%; step-families: 4.3% *vs*. 10.3%), and had fewer immigrant families (47% *vs*. 57.7%; Meunier, Boyle, O'Connor, & Jenkins, 2013). According to the 2011 National Household Survey (NHS), the make-up of the immigrant population in Toronto (% of total population) is: 12.7% East Asian (Chinese, Korean, Japanese), 12.3% South Asian, 8.5% Black, 7.0% Southeast Asian, 5.1% Filipino, 2.8% Latin American, 2.0% West Asian, 1.1% Arab, 0.7% Aboriginal, 1.5% Multiracial, and 1.3% Other.

Only children with birth weights ≥ 2500 g and gestational ages ≥ 37 weeks were included to limit the sample to non-premature and non-LBW children. There were 21 children (4.2%) born under 2500 g and 20 children (4.0%) born under 37 gestational weeks. Exclusion of these children resulted in a final sample of 468 children (93.4% of total sample). For outcome measures at 3 and 4.5 years (child language, EF, and ToM), there were variable levels of missing data due child noncompliance, administration error (e.g., the study interviewer did not follow the standardized protocol), or family limitations (running out of time). Table 2 shows data availability for all measures across time points.

Table 1. Demographics of sample ($N = 468$) at study entry

Measure	*N*	% of sample
Ethnicity of mothers	468	100.0
European/Caucasian	267	57.1
South Asian	62	13.2
East Asian	56	12.0
Black	39	8.3
Other	44	9.4
Teen mom	29	6.3
Non-intact family	53	11.3
New-immigrant family (<10 years)	213	45.5
Low income family (< $20,000)	37	8.4
Mother's years of education (< high school)	78	16.7
Mothers scoring in depressed range on CES-D	73	15.8
Infant birth weight <2500 g[a]	18	3.6
Gestational age < 37 weeks[a]	20	4.0

CES-D = Center for Epidemiological Studies Depression Scale.
[a]As the sample excluded those born < 2500 g and at < 37 weeks gestation, these values reflect the number of children in the overall sample at study entry ($N = 501$).

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Table 2. Descriptive statistics for study variables

Measure	T1				T2				T3				T4			
	M	*SD*	*N*	*Range*	*M*	*SD*	*N*	*Range*	*M*	*SD*	*N*	*Range*	*M*	*SD*	*N*	*Range*
Birth weight	3.47	.45	468	2.5–5.0	—	—	—	—	—	—	—	—	—	—	—	—
Gestational age	39.2	.95	468	37–40	—	—	—	—	—	—	—	—	—	—	—	—
Age	.17	.09	468	.00–.58	1.60	.16	379	2.5–4.5	3.15	.27	362	2.5–4.5	4.78	.28	306	3.8–5.8
Gender			468				379				362				307	
Male	—	—	238	—	—	—	200	—	—	—	186	—	—	—	150	—
Female			230				179				176				157	
Maternal education	15.4	2.6	468	8–22	15.6	2.6	321	10–22	15.6	2.5	303	8–22	15.5	2.4	214	10–22
Canadian-born			468													
Yes	—	—	255	—	—	—	—	—	—	—	—	—	—	—	—	—
No			213													
Number of kids	2.38	.84	468	2–10	2.38	.79	379	2–10	2.56	.90	362	2–10	2.58	.87	307	2–10
Language (PPVT)	—	—	—	—	—	—	—	—	94.9	15.2	284	49–137	—	—	—	—
Executive function	—	—	—	—	—	—	—	—	—	—	—	—	.01[a]	.81	295	—
Theory of mind	—	—	—	—	—	—	—	—	—	—	—	—	3.7	1.5	286	0–7

Note. PPVT = Peabody Picture Vocabulary Test – Third Edition.
[a]These variables are Z-scored or standardized composites, which explains the mean centered at zero.

Attrition Analysis

Attrition analysis was conducted in which participants remaining in the sample at T4 were compared to those who dropped out on key demographic variables measured at study entry. Compared to families that remained in the sample at T4, those who dropped out were comparable on family structure (i.e., intact *vs*. non-intact family), χ^2 (df = 1) = 3.30, p = .083, clinical levels of maternal depression, χ^2 (df = 1) = 3.52, p = .080, whether the mother was an immigrant, χ^2 (df = 1) = .85, p = .38, teenage motherhood, χ^2 (df = 1) = 4.15, p = .067, and family income < $20 000, χ^2 (df = 1) = 2.19, p = .15. Families who dropped out were more likely than those who did not participate to have mothers with less than high school education, χ^2 (df = 1) = 7.05, p = .009. Using birth weight and gestational age as continuous measures, there were no differences between those who remained at T4 *versus* those who dropped out on birth weight, t(466) = -.71, p = .48, or gestational age, t(466) = .54, p = .59. Also, there were no differences on T3 language (receptive vocabulary) for those who dropped out from T3 to T4, t(282) = .79, p = .43.

Procedure

At each time point, a home visit of approximately two hours involved questionnaires related to prenatal and pregnancy information (T1 only) as well as demographics and family life. Children's neuropsychological abilities (Language, ToM, and EF) were also directly assessed using age-appropriate standardized and/or observational tasks.

Measures

Birth weight

At T1, mothers reported their newborn's birth weight in kilogram and grams. This score was normally distributed across the normal birth weight range (≥2500 g).

Gestational age

At T1, mothers reported the number of gestational weeks of the child.

Language (T3)

The *Peabody Picture Vocabulary Test – Third Edition* (PPVT; Dunn & Dunn, 1997) was used to assess children's language ability at T3. The PPVT is a standardized measure of receptive vocabulary skills for children aged ≥ 2 years. Children are required to point to a picture that corresponds to the stimulus word among a bank of four picture options. The PPVT has been shown to be adequately reliable and valid (Dunn & Dunn, 1997).

Executive Functioning (T4)

This was assessed using the Bear/Dragon task (Reed, Pien, & Rothbart, 1984) and the Dimensional Change Card Sort

(DCCS; Zelazo, 2006), two of the best-validated and most widely used tasks for the assessment of EF in the current age group (Blair, Zelazo & Greenberg et al., 2005; Carlson, 2005; Carlson, Mandell & Williams, 2004). We followed Carlson's (2005) measurement guidelines for maximizing detection of age-dependent individual differences in inhibitory control, set shifting, and working memory. For the *Bear/Dragon* task, children were instructed to do what they were told by the nice bear (e.g., "touch your nose"), but not to do what they were told by the mean dragon. Children were scored for total number of correct responses on five dragon and five bear trails (0–10). This task has been shown to be highly correlated with other executive function tasks (Carlson et al., 2004) and to relate well to expected child and context factors (Sabbagh, Xu, Carlson, Moses, & Lee, 2006). For the DCCS, children were required to sort a series of bivalent test cards, first according to one dimension (e.g., color), and then according to the other (e.g., shape). Children who pass the post-switch phase of the standard version of the DCCS may proceed immediately to the border version, which uses the same target cards as the standard version. The border version consists of 12 trials. Children are required to sort cards based on "border" criteria ("If there's a border, play the color game. If there's no border, play the shape game"). Previous studies have shown that Bear/Dragon and DCCS load onto the same latent factor measuring set shifting, working memory, and inhibitory control (Bernier, Carlson, Deschênes, & Matte-Gagné, 2012) and in the current study were also significantly correlated, $r = .34$, $p < .001$. Consequently, they were *Z*-scored and averaged into a composite measure of EF. Higher scores represented better EF ability.

Theory of mind (ToM)

ToM was measured using the scale described by Wellman and Liu (2004), representing the most comprehensively validated test of ToM (Sabbagh & Seamans, 2008), including validation across cultures, languages, and in both typically and atypically developing children (Peterson, Wellman, & Slaughter, 2012). ToM has been found to be stable over time (Jenkins & Astington, 2000). The Wellman and Liu (2004) scale presents various tasks sequentially in a manner that maps onto the children's theory of mind development. As children move through the scale, tasks become conceptually more difficult. Thus, progression further along the scale reflects more sophisticated ToM understanding. The first three tasks assessed children's understanding of diverse desires and beliefs, and knowledge and ignorance, followed by tasks assessing more sophisticated ToM understanding such as belief-based emotion, and real-apparent emotion. If children failed two consecutive tasks, testing was stopped. For all tasks, stories were enacted for children with the use of puppets and props. A total score across all tasks (pass/fail) was computed. Internal consistency was high, $\alpha = .87$.

Covariates

These included the child's current age (in years), gestational age (in weeks), and gender (0 = male; 1 = female). Socioeconomic status (SES) was assessed *via* both maternal education (in years) and annual family income assessed on a scale from 1 ("no income") to 16 ("$105 000 or more"), reported by the mother. Also included was the Canadian-born status of the mother as a dichotomous variable (0 = no; 1 = yes), and the number of children in the home, as this has been shown to impact cognitive outcomes.

Analysis Plan

The analysis was carried out using Mplus version 7.0 (Muthén & Muthén, 2010). Path analysis was used to examine the total, direct, and indirect effects hypothesized above. The *total effect* (*c* path) is a measure of the effect of birth weight on the outcome (EF or ToM) without inclusion of the mediator (language). The *direct effect* (*c'* path) is the effect of birth weight on the outcome after in inclusion of the mediator. The *indirect effect* (*ab* path) is the effect of birth weight on the outcome through the hypothesized mediator, and is thus the product of the effect of birth weight on language (*a* path) and language on the outcome (*b* path). Indirect effects were tested using the delta method (Sobel, 1982), which is the default in Mplus. These paths were tested simultaneously for both ToM and EF, thereby providing unique estimates for each outcome. The delta method calculates the standard error of the product of two variables, which can then be used to determine the significance of the indirect path. This method is used in applied statistics to obtain approximate standard errors and confidence intervals of parameters in path analysis and basic structural equation models (Raykov & Marcoulides, 2004). Since covariates are not readily available in viewing the path model, we also present the full regression results for the path model that include all covariates. In these regression models, all variables were entered simultaneously, and thus control for all other effects in the model. We report standardized effects for all results.

Full information maximum likelihood estimation (FIML) was used for all analyses. This method offers improvements over traditional approaches for handling missing data such as listwise deletion, pairwise deletion, and imputation in terms of parameter bias, model convergence and fit (Acock, 2005; Enders & Bandalos, 2001). FIML can handle up to 50% missing data without biasing the estimates (Graham & Schafer, 1999). The estimator used was a maximum-likelihood with robust standard errors (MLR) estimator, which produces parameter estimates with standard errors and a χ^2 that are robust to non-normality when missing data are present (Muthén & Muthén, 2010). For model fit, we report the root-mean-square-error of approximation (RMSEA), comparative fit index (CFI), Tucker-Lewis index (TLI), and standardized root-mean-square residual (SRMR).

RESULTS

Descriptive statistics, including means, standard deviations, variable frequencies, and ranges for study variables across

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Table 3. Bivariate associations between study variables

Measures	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
1. Birth weight	—									
2. Gestation age	.24***	—								
3. Child age	.02	.00	—							
4. Female gender	−.13**	.11*	−.05	—						
5. Maternal education	.03	.12*	.00	−.04	—					
6. Family income	.09†	.03	.05	.02	.49***	—				
7. Canadian-born status	.11*	−.02	.23***	−.01	.13**	.33***	—			
8. Number of kids in home	.04	−.09†	−.01	−.02	−.16**	−.19**	.06	—		
9. Language (T3)	.16**	.06	.14*	.07	.15*	.40***	.29***	−.12*	—	
10. Executive function (T4)	.12*	−.10†	.24***	.01	.10†	.17**	.15*	−.06	.32***	—
11. Theory of mind (T4)	.10†	.09	.22***	.15*	.13*	.15*	.11†	−.04	.27***	.33***

†p < .10.
*p < .05.
**p < .01.
***p < .001.

time are presented in Table 2. Table 3 presents the bivariate relationships between study variables. Notable associations include the relationship between family income and maternal education with all child outcomes (T3 language and T4 EF and ToM), and significant inter-relations among all neuropsychological skills. Unsurprisingly, child age was associated with all neuropsychological outcomes, with older children performing better across tasks. Females performed significantly better than males on T4 ToM tasks. The Canadian-born status of the mother was also related to all child outcomes, with the children of Canadian-born mothers having higher skills across neurocognitive domains. The number of children in the home was negatively associated with maternal education and family income, as well and children's language ability at T3. Birth weight was positively associated with children's language at T3, their EF at T4, and marginally associated with ToM ability at T4.

Table 4 presents the final regression results from the path analysis for child language at T3 (age 3) and EF and ToM at T4 (age 4.5). For T3 language, higher family income [β (SE) = .30 (.10), p = .002], having a Canadian-born mother [β (SE) = .20 (.08), p = .007], fewer children in the home [β (SE) = -.15 (.05), p = .005], and being higher birth weight [β (SE) = .17 (.07), p = .012] were significant predictors of higher receptive vocabulary at age 3. This model explained 24% of the variance in child language. For EF, older age [β (SE) = .18 (.06), p = .001] and higher language at T3 [β (SE) = .32 (.09), $p < .001$] were the only significant predictors of higher EF at age 4.5. This model explained 18% of the variance in EF. Finally, for ToM, female gender [β (SE) = .19 (.06), p = .003] and higher T3 language [β (SE) = .27 (.08), p = .001] were the only significant predictors of higher ToM at age 4.5. This model explained 15% of the variance in ToM.

Table 4. Regression results for mediator (language) and outcome (EF and ToM) variables.

	1. Language (T3)		2. Executive function (T4)		3. Theory of mind (T4)	
Predictors	STD (SE)	R^2	STD (SE)	R^2	STD (SE)	R^2
Child age	.01 (.06)		.18 (.06)**		.13 (.07)†	
Female gender	.04 (.06)		.06 (.06)		.13 (.06)*	
Maternal education	−.04 (.09)		.06 (.08)		.14 (.08)†	
Family income	.30 (.10)**		−.01 (.07)		−.05 (.08)	
Canadian-born status	.20 (.08)**	.24***	−.01 (.06)	.18**	−.04 (.08)	.15**
Number of kids in home	−.15 (.05)**		−.02 (.05)		.04 (.05)	
Gestational age	−.06 (.07)		−.11 (.06)†		.06 (.06)	
Birth weight	.17 (.06)**		.10 (.05)†		.08 (.07)	
Language	—		.33 (.10)***		.30 (.07)***	

Note: STD = standardized parameter estimate; SE = standard error; Model 1 = Language at T3; Model 2 = Executive function at T4; Model 3 = Theory of mind at T4
†p < .10.
*p < .05.
**p < .01.
***p < .001.

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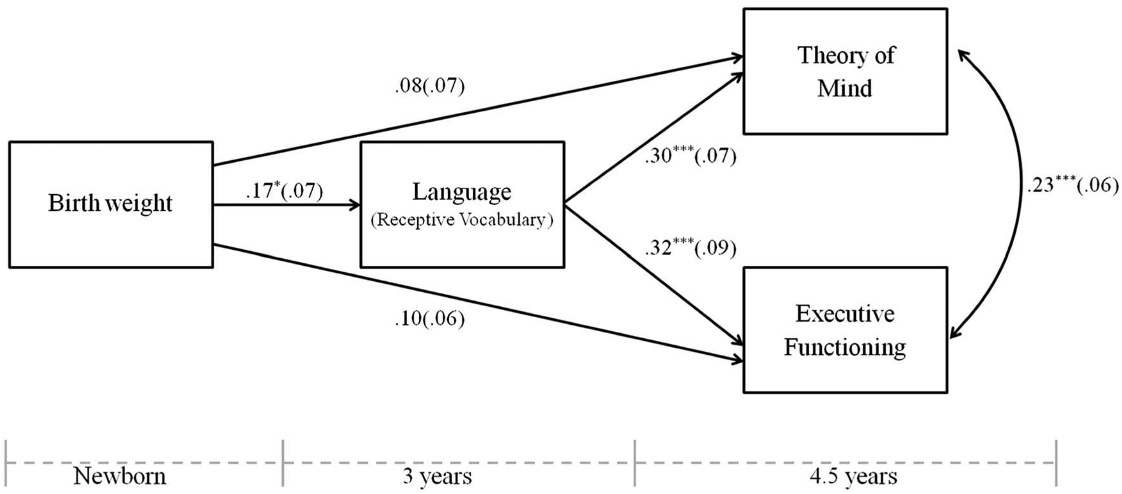

Fig. 1. Path model for the hypothesized indirect effect of birth weight on theory of mind (ToM) and executive functioning (EF) at age 4.5 through child language (receptive vocabulary) measured at 3 years. Estimates are standardized coefficients (standard errors presented in brackets). All parameters control for covariates. Effects from birth weight to ToM and EF are direct effects after inclusion of mediator (i.e., language); see in-text for total and indirect effect estimates. †$p < .10$; *$p < .05$; **$p < .01$; ***$p < .001$

Indirect effects of birth weight on EF and ToM at T4 through language at T3 were examined next. First, model fit was excellent in accordance with recommended criteria of Hu and Bentler (1999): RMSEA = .016, CFI = .99, TLI = .98, and SRMR = .014. For ToM, the total effect was significant [β (SE) = .13 (.07), p = .05], meaning that, without child language in the model, higher birth weight significantly predicted higher ToM. Upon inclusion of child language at T3, the direct effect from birth weight to ToM was reduced to non-significance [β (SE) = .08 (.07), p = .23]. Also, the indirect effect of birth weight on ToM through child language was significant (z = 2.05; p = .041), suggesting that language at age 3 mediates the relationship between birth weight and ToM at age 4.5. The standardized indirect effect size (a*b) was .050, which corresponds to a small to medium effect.

For EF, the total effect was significant [β (SE) = .15 (.06), p = .008], meaning that birth weight shows an association with EF when language is not included in the model. Upon inclusion of language at T3, the direct effect was reduced to non-significance, but continued to show a marginal association with EF [β (SE) = .10 (.06), p = .08]. The indirect effect of birth weight on EF through child language was significant (z = 2.07, p = .038), suggesting that the effect of birth weight on EF at age 4.5 operates (at least partially) indirectly through language ability at age 3 (see Figure 1). The standardized indirect effect size (a*b) was .054, which is a small to medium effect.

DISCUSSION

The current study used a prospective community birth cohort to examine the relationship between normal birth weight variation (≥2500 g) and children's neuropsychological outcomes, and a potential mechanism linking the development of these skills over time. After controlling for a variety of potential confounding variables, it was demonstrated that birth weight was positively associated with children's language ability (indexed their receptive vocabulary) at age 3, as well as their EF and ToM abilities at age 4.5. These results are consistent with previous reports showing that birth weight variation within the normative range is associated with a host of child outcomes such as IQ, academic abilities, and executive control (Kirkegaard et al., 2006; Matte et al., 2001; Noble, Fifer, Rauh, Nomura, & Andrews, 2012; Phua et al., 2012). The current study builds on past findings by showing that the effect of birth weight on children's EF and ToM in the preschool period is mediated by their language skills at age 3, suggesting that lower birth weight within the normal range may disrupt the optimal development of key language skills that serve as important predictors of emerging neuropsychological abilities.

The acquisition of language, EF, and ToM is especially salient in the preschool period, as this coincides with the transition of most children into kindergarten. This is important because children entering this stage of life who have mastered these neuropsychological skills are more likely to show favorable social outcomes (Razza & Blair, 2009), academic competence (Blair & Razza, 2007; Hughes & Ensor, 2011), lower levels of aggression (Olson, Lopez-Duran, Lunkenheimer, Chang, & Sameroff, 2011), and fewer internalizing and externalizing problems (Hughes & Ensor, 2007b, 2008, 2011). Many previous studies have documented the deleterious effect of LBW on various psychiatric conditions and developmental disorders, and recent studies have extended these findings into the normal birth weight range. The current study continues efforts to uncover the neuropsychological endophenotypes that potentially underpin these adverse outcomes (Hatch et al., 2014; Phua et al., 2012).

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Although more research is needed, this study supports previous findings and further implicates ToM as another cognitive ability that may be influenced by perinatal factors such as birth weight. As such, children with birth weights at the lower end of the normal range who have greater difficulty with EF and ToM may show difficulties across a range of associated psychosocial outcomes that rely on these critical neuropsychological skills.

Moreover, the current results speak to the important mediating role of language in EF and ToM development. The robust effect of birth weight on children's language, in conjunction with the foundational role of language in the development of other cognitive abilities (Bickerton, 2005; Fernyhough, 2008), is consistent with these findings. Indeed, intervention studies show that language-based training programs have the effect of fostering both linguistic knowledge and ToM ability (Hale & Tager-Flusberg, 2003), which speaks to the causal role of language in ToM development (also see Astington & Jenkins, 1999). In addition, the provision of early verbal input from caregivers has been shown to influence later executive processing skills through children's intermediary language ability in early and middle childhood (Landry, Miller-Loncar, Smith, & Swank, 2002; Matte-Gagné & Bernier, 2011). Taken together, these results suggest that language may be an essential cognitive ability linking birth weight variability to individual differences in EF and ToM in the preschool period.

In general, the current results are consistent with the notion that birth weight variability and resultant neuropsychological competencies should be considered along a phenotypic continuum. Importantly, however, the mechanisms connecting birth weight to neurocognitive outcomes may be different for children within the normative range compared to those classified as (V)LBW, who typically face more medical complications such as hypoxia-ischemia, infection, and periventricular leukomalacia (Stoll et al., 2004; Vohr et al., 2000). These conditions are characterized by cortical gray matter and white matter reductions (Inder et al., 1999), which are believed to underlie the cognitive and behavioral deficits observed in these infants (Rezaie & Dean, 2002). Of interest, studies of normal birth weight children also show that higher birth weight is related to increases in gray and white matter volume (Raznahan, Greenstein, Lee, Clasen, & Giedd, 2012; also see Davis et al., 2011 for similar effects across the normal gestational age range). Furthermore, for normal birth weight children, findings are suggestive of cortical variability in brain regions that have been previously implicated in language, ToM, and EF, including anterior cingulate, orbitofrontal, and temporo-parietal areas (Walhovd et al., 2013). Thus, relatively small differences in birth weight across the normal range may represent critical sources of inter-individual variability in neural functioning that support neuropsychological development. Nevertheless, it remains unclear whether the precise neural and physiological mechanisms linking birth weight to neurocognitive functioning are the same or different for (V)LBW compared to normal birth weight children. Additional factors such as antenatal stress, nutrition, parity, and lifestyle factors including smoking and alcohol use may be important contributors for children in either the (V)LBW or normative range (Breeze & Lees, 2007). Future studies specifying and differentiating these mechanisms will improve our understanding of the unique pathways to children's neuropsychological health and development.

Strengths and Limitations

The current findings should be considered in light of study strengths and limitations. The strengths included a prospective, longitudinal design, large and diverse sample, and use of well-validated, standardized tasks. Inclusion of potential prenatal and postnatal confounding variables also adds to the robustness of the current findings. Importantly, the effects demonstrated in the current study were significant and in line with study hypotheses, but were generally small in magnitude. Thus, the effect of birth weight on neuropsychological skills in the normative range of development should be considered small. Further replication is important. Regarding limitations, the first is that our measure of language at age 3 was a single measure of receptive vocabulary, and this may not approximate the complexity of children's language at this stage. Although PPVT is one of the most widely used measures of language in the developmental literature (especially in relation to ToM and EF), future studies using a more comprehensive measure could provide a more nuanced view of the language functions affected. We also cannot rule out the possibility that this measure of language was indexing more general cognitive abilities (e.g., overall IQ) at this stage, and future studies that control for additional verbal and non-verbal cognitive skills may prove useful in determining the specific role of language as a mediator of the link between birth weight and ToM/EF. Second, our sample enlisted and retained families that were more educated than the general population (de Graaf, Bijl, Smit, Ravelli, & Vollebergh, 2000). We also recruited families with at least one older child. These sampling factors may limit the generalizability of our findings. Also, there was a variable amount of missing data on the outcome measures due to attrition and non-response. Best practice approaches to the handling of missing data were used (Graham, 2009), but caution should still be exercised when interpreting these results.

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