

IQ, fetal testosterone and individual variability in children's functional lateralization

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ABSTRACT

Previous event-related potential (ERP) studies have revealed that faces and words show a robust difference in the lateralization of their N170. The present study investigated the development of this differential lateralization in school-age boys. We assessed the potential role of fetal testosterone (FT) level as a factor biasing the prenatal development of lateralization, and the role of reading skill and Verbal IQ as factors predicting left lateralization for words in childhood. The adult pattern of differential N170 lateralization for faces and words was not present in a group of 26 school-age boys. This suggests that N170 lateralization only appears with years of experience with these stimulus categories or with late childhood maturation. FT level measured by amniocentesis did not account for a significant part of the individual variability in lateralization. Verbal IQ correlated with the degree of left lateralization of the N170 to words, but this effect was not specific to language abilities and language lateralization. A strong correlation was observed between the degree of left lateralization for words and the degree of left lateralization for faces, and both lateralization scores correlated with Verbal and Performance IQ. Possible explanations for these results are discussed along with ERP correlates of words and faces in school-age boys.

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In order to understand the mechanisms that lead to the functional specialization of brain areas, and to what extent this pattern is pre-determined, researchers have been studying whether lateralization of cognitive functions is present from birth. Some studies have provided evidence that functional lateralization is present to a certain degree several months after birth (de Haan & Nelson, 1999; de Schonen & Mathivet, 1990; Dehaene-Lambertz, Dehaene, & Hertz-Pannier, 2002; Entus, 1977; Friederici, 2006; Tzourio-Mazoyer et al., 2002), suggesting that prenatal factors could bias each hemisphere to specialize for certain cognitive functions. However, the study of patients with early unilateral brain lesions (Bates & Roe, 2001; Dick, Wulfeck, Krupa-Kwiatkowski, & Bates, 2004), as well as electrophysiology and functional imaging studies with infants and children (de Haan, Pascalis, & Johnson, 2002; Halit, 2002; Maurer, Brandeis, & McCandliss, 2005; Maurer, Brem, Bucher, & Brandeis, 2005; Maurer et al., 2006; Mills et al., 2004; Pugh, Sandak, Frost, Moore, & Mencl, 2005; Schlaggar et al., 2002; Taylor, Batty, & Itier, 2004) suggest that lateralization evolves during

infancy and childhood to eventually achieve the adult pattern. The present study investigated the factors that contribute to this development of functional lateralization for faces and for words. It had two aims: (1) to assess the potential role of fetal testosterone (FT) as a factor biasing the development of lateralization prenatally and (2) to assess the potential role of reading skill and Verbal IQ as factors predicting left lateralization for words in childhood.

In this study, functional lateralization was measured using event-related potentials (ERPs). Previous studies have shown that the N170 ERP component differs in lateralization for words and faces (Joyce & Rossion, 2005; Mercure, Dick, Halit, Kaufman, & Johnson, 2008; Rossion, Joyce, Cottrell, & Tarr, 2003), with a larger amplitude in the left than right hemisphere for words (Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999; Brem et al., 2005; Joyce & Rossion, 2005; Maurer, Brandeis, et al., 2005; Maurer, Zevin, Hulse, & McCandliss, 2007; Rossion et al., 2003; Wong, Gauthier, Woroch, DeBuse, & Curran, 2005) and a tendency for a larger amplitude in the right than left hemisphere for faces (Bentin, Allison, Puce, Perez, & McCarthy, 1996; Bentin & Deouell, 2000; Bentin, Golland, Flevaris, Robertson, & Moscovitch, 2006; Boutsen, Humphreys, Praamstra, & Warbrick, 2006; Caldara, Rossion, Bovet, & Hauert, 2004; de Haan et al., 2002; Rossion et al., 2003). This measure was chosen as an index of functional lateralization since it has been replicated many times in adults and because it shows

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individual variability. Based on previous studies (Maurer, Brem, et al., 2005; Maurer et al., 2006; Taylor et al., 2004), this variability was expected to be even greater in children, possibly reducing the differential lateralization between categories to non-significance at the group level.

1. Fetal testosterone (FT) as a prenatal factor biasing lateralization

An influence of FT on brain lateralization was initially proposed in the early 1980s (Geschwind & Behan, 1982, 1984). The Geschwind–Behan–Galaburda (GBG) model suggested that the level of prenatal testosterone influences the rate of neuronal migration from the neural crest into the cortex, especially in the left hemisphere. A high level of FT would lead to retardation in the growth of the left hemisphere, and possibly left hemisphere abnormalities. This would prevent the establishment of left lateralization of cognitive functions and affect the development of language. Elevated FT would also have a suppressive effect on the thymus, affecting the maturation of the immune system and increasing the incidence of various immune diseases. The GBG model has been criticized because many of the predicted statistical associations were not reliably observed (Berenbaum & Denburg, 1995; Bryden, McManus, & Bulman-Fleming, 1994; Forget & Cohen, 1994; Obrzut, 1994; Previc, 1994). The evaluation of each of these associations is beyond the scope of this paper and only the predicted association between high prenatal testosterone and ‘anomalous dominance’ will be discussed. An alternative theory linking FT and lateralization is the callosal hypothesis, which states that brain lateralization results from the pruning of cells in the corpus callosum during the fetal and neonatal period, and that this process is influenced by testosterone levels during this period (Witelson & Nowakowski, 1991). This theory suggests that high levels of FT increase the pruning of callosal cells, which in turn decreases the connectivity between the hemispheres, and increases lateralization of brain functions. This hypothesis emerged from the author’s observation that left-handed and ambidextrous individuals have a larger corpus callosum compared to right-handed individuals (Witelson, 1985).

The literature that empirically tests these models is highly variable, with evidence consistent with both the GBG model (Kelso, Nicholls, Warne, & Zacharin, 2000), and the callosal hypothesis (Cohen-Bendahan, Buitelaar, van Goozen, & Cohen-Kettenis, 2004; Grimshaw, Bryden, & Finegan, 1995) as well as evidence showing no support for an influence of FT on lateralization (Helleday, Siwers, Ritzen, & Hugdahl, 1994; Mathews et al., 2004). Since the testosterone level in the fetal blood cannot be directly accessed in humans, research teams have developed various methods of estimating this value and its impact on brain development. For example, some have studied genetic disorders associated with a high level of FT (Helleday et al., 1994; Kelso et al., 2000; Mathews et al., 2004), or studied female fetuses developing in the proximity of a male twin (Cohen-Bendahan et al., 2004). In addition, the concept of lateralization itself differs from one author to another and methods for measuring lateralization are extremely varied. Indeed, one major criticism of the GBG model is that the authors did not precisely define the term ‘anomalous dominance’, which in the theoretical model seemed to correspond to the organization of language in the hemispheres. However, many studies used handedness as the indicator of dominance when testing the model, despite the fact that only a modest association is found between these two variables (Bryden et al., 1994). What the literature lacks is a comparison between a prenatal measure of testosterone level and lateralization for cognitive functions assessed by a measure of brain activity.

In the present study, FT level was assessed by amniocentesis since this method is the most direct way of measuring hormonal levels in the fetal period (Cohen-Bendahan, van de Beek,

& Berenbaum, 2005; Finegan, Bartleman, & Wong, 1989). Amniocentesis is a routine medical procedure used for prenatal diagnosis, whereby a long syringe guided by ultrasound is inserted through the mother’s abdominal wall to extract a small amount of amniotic fluid. The level of testosterone in the amniotic fluid is uncorrelated with maternal levels of circulating testosterone (van de Beek, Thijssen, Cohen-Kettenis, van Goozen, & Buitelaar, 2004) and is believed to reflect the true level of fetal exposure (Baron-Cohen, Lutchmaya, & Knickmeyer, 2004; Finegan et al., 1989). The children who participated in the present study were recruited from a larger cohort followed longitudinally (Baron-Cohen et al., 2004). In this cohort, FT level has been found to predict several aspects of development, such as frequency of eye contact between infants and their parents at 12 months (Lutchmaya, Baron-Cohen, & Raggat, 2002a), vocabulary size at 18 and 24 months (Lutchmaya, Baron-Cohen, & Raggat, 2002b), and quality of social relationships and restrictive interests at 4 years (Knickmeyer, Baron-Cohen, Raggat, & Taylor, 2005). Only boys participated in the present study as the literature suggests that the influence of testosterone on behavior may differ in males and females, with more consistent influences observed in boys than girls (Knickmeyer et al., 2005; Knickmeyer, Baron-Cohen, Raggat, Taylor, & Hackett, 2006; Lutchmaya et al., 2002a). Boys also show greater variability in their FT level, which increases the potential sensitivity of the study. The first aim of this study was to investigate whether FT level accounts for a significant amount of the individual variability in lateralization of the N170 to words and faces.

2. Reading skill and Verbal IQ as factors predicting left lateralization for words

As mentioned earlier, there is consistent evidence to support the idea that lateralization continues to develop late into childhood, but the mechanisms underlying the establishment of this pattern are unclear. One possibility is that lateralization is reinforced as skill or expertise develops for one domain. Functional imaging studies in typically developing children have shown a correlation between reading skill and activity in the occipitotemporal region of the left hemisphere, while several right hemisphere areas showed an age- or skill-related decrease in activity (Pugh et al., 2005). Moreover, children with reading disorders usually show less activity in the left occipitotemporal region, with increased activity in its right hemisphere homologue (Pugh et al., 2005). In ERPs, skilled adult reading is reflected by the functional specialization of the N170 component, which is larger for words than for perceptually equivalent symbol strings, and left lateralized at the group level (Bentin et al., 1999; Brem et al., 2005; Joyce & Rossion, 2005; Maurer, Brandeis, et al., 2005; Maurer et al., 2007; Rossion et al., 2003; Wong et al., 2005). In kindergarten children who could not yet read, it was observed that the N170 did not differ between words and symbols and was not lateralized (Maurer, Brem, et al., 2005). After these children learned basic reading skills (in 2nd grade), the N170 was larger for words than for symbol strings, but was not lateralized at the group level (Maurer et al., 2006). Even if left functional lateralization was previously observed in infants and children performing different language tasks (Balsamo, Xu, & Gaillard, 2006; Dehaene-Lambertz et al., 2002; Friederici, 2006), these results suggest that left lateralization of the N170 for written words appears with years of experience with reading and possibly relates to reading skill. In face processing, right lateralization of the N170 is not consistently found at the group level before 12–13 years old (Taylor et al., 2004), although it is not yet clear what factors influence the establishment of this pattern.

The second aim of this study was to investigate whether a significant amount of the individual variability in lateralization of the N170 for words could be accounted for by reading skills (assessed by

the Test of Word Reading Efficiency—TOWRE) or by verbal abilities (assessed by Verbal IQ). The acquisition of a specific skill through training (for example, reading) is influenced by an individual's set of more general and more stable abilities (for example, verbal abilities) (Fleishman, 1966). Testing the influence of both reading skills and verbal abilities could help differentiate the impact of a recent skill acquisition process from more stable individual differences. In order to find if this potential link was restricted to language lateralization and language abilities, we also examined the potential relationship between the degree of lateralization for faces and these measures of verbal abilities and reading skills, as well as between the degree of lateralization for words and Performance IQ.

This study also explored how lateralization for one domain (word processing) relates to lateralization for another domain (face processing) within an individual. Does the development of lateralization for one domain predict, inhibit or interact with the development of lateralization for another domain? Because of the different developmental trajectories of face and written word processing, an expertise account of lateralization would not predict a strong relationship in the degree of lateralization of these two domains.

These analyses aim to find factors that correlate with lateralization, but do not suggest that any of these factors *cause* lateralization. Indeed, it is possible that developing a new skill increases lateralization, and it is also possible that an increased lateralization favors the development of specific skills. Moreover, the direction of the relation might not even be unidirectional. As described by probabilistic epigenesis theory, there might be reciprocal influences between the development of the structure and functions of the brain (Gottlieb, 1998, 2007).

3. Methods

3.1. Participants

26 boys between 7 and 10 years old (mean = 8 years and 5 months) were recruited from the Cambridge Fetal Testosterone Project to take part in this ERP study (Baron-Cohen et al., 2004). None of these children had any current or previous diagnosis of speech, language, reading, learning or neurological deficit, and all had good or corrected eyesight according to parental report. Five were left-handed based on preferred writing hand. Handedness was confirmed by a modified version of the Edinburgh Handedness Inventory in 24 out of 26 children. All had English as their first language. Their Verbal and Performance IQ scores (Wechsler Abbreviated Scale of Intelligence) were in the normal range, with scores ranging between 80 and 127. Standardized scores on the Test of Word Reading Efficiency (TOWRE Subtest 1: Sight Word Efficiency¹) ranged from 83 to 134. These scores qualified most of these children as above average (20 children), whereas only two children scored slightly below average. FT level of the amniotic fluid was measured by amniocentesis between weeks 14 and 22 of gestation. All of the amniocentesis procedures were performed at hospitals in the East Anglia area of the UK upon referral of the mother. Reasons for referral included: elevated risk of genetic disorder as indicated by the Triple Test (60%); maternal age over 35 years old (25%); family history of Down's Syndrome (2.5%); maternal anxiety (3.75%); or markers of Down's Syndrome identified on scan (8.75%). FT levels were measured using radioimmunoassay in the Department of Clinical Biochemistry of Addenbrooke's Hospital and ranged from 0.13 to 1.75 (mean = 0.73 nmol/l) for these 26 boys. These values closely resemble those found with larger cohorts sourced from the Cambridge Fetal Testosterone Project (Baron-Cohen et al., 2004). Birkbeck School of Psychology Ethics Committee and Addenbrooke's Hospital Local Research Ethics Committee approved this project and this study has been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

3.2. Stimuli and procedure

The stimuli and procedure were similar to those previously used in an ERP study with adults (Mercure, Dick, Halit, & Johnson, 2007; Mercure et al., 2008). Stimuli were grayscale pictures of faces and words on a rectangular background. All stimuli subtended 5° × 6.5° of visual angle from a viewing distance of 57 cm.

Each category was composed of 60 exemplars, with an additional 8 per category as practice items. Faces all depicted Caucasian females² with a direct gaze and a neutral facial expression, displayed on a white background with the eyes occupying the center of the picture. Stimuli were adapted from the face databases of the Centre for Brain and Cognitive Development, the Nim Stim Face Stimulus Set³ and the CVL Face Database (Solina, Peer, Batagelj, Juvan, & Kovae, 2003). Word stimuli were presented in uppercase black Arial capital font on a grey background, and were 5-letter nouns with 4–5 phonemes, 1–2 syllables and one morpheme. Words were rated between 200 and 600 for familiarity, concreteness and imageability (on a rating ranging from 100 to 700), had 8 or less orthographic neighbors (MRC Psycholinguistic Database: Wilson, 1987), and had a written frequency of occurrence between 20 and 150 per million words (Kucera & Francis, 1967). Frequency of appearance in texts read by grade 1 and grade 2 children totaled between 12 and 578 according to Zeno (1995).

Children performed a 'one-back' memory task, pressing a joystick key every time they thought that a stimulus had been presented twice in a row. 10 practice items (8 stimuli, 2 targets/repetitions) were presented at the beginning of each block, and participants repeated practice blocks if their button press accuracy was <90% (including false alarms). Experimental blocks were composed of 35 trials (30 stimuli, 5 repetitions/targets), which is half the length of the blocks presented in the adult study (Mercure et al., 2007, 2008). Two experimental blocks of words and two experimental blocks of faces were presented in counterbalanced order, giving the same total number of trial per category as in the adult study. Each trial began with a 700-ms presentation of a stimulus in the middle of the screen, followed by a 1350-ms response window. A fixation cross was present during this response window and participants were instructed to keep their gaze at the location of this cross at all times. Trials that represented a repetition of stimuli (targets) and those where participants responded incorrectly (e.g., false alarms) were eliminated from analyses, leaving only response-free trials. In the same visit, children also participated in another ERP study, which was counterbalanced in order with the present study.

3.3. ERP recording and analysis

EEG signal was recorded using a Geodesic Sensor Net with 128 electrodes (Tucker, 1993), with vertex as reference. Horizontal and vertical electro-oculograms were used to monitor eye movements. EGI NetAmps 200 was used (gain = 1000), and data were digitized with sampling rate of 250 Hz, and band-pass filtered between 0.1 and 100 Hz.

Each trial was segmented from the continuous EEG data (windowed from 200 ms pre-stimulus onset to 600 ms post-stimulus onset). Segments were individually inspected for artifacts including blinks and eye movements. The 'bad channel replacement' algorithm in Net Station 4.2 was used to replace the signal from rejected electrodes with a signal interpolated from the remaining channels using spherical splines. If more than 10 of 128 channels were rejected, the trial was not included in the condition average. For each participant, a minimum of 40 trials was included in each category's average. Waveforms were baseline-corrected using the 200-ms pre-stimulus interval. Averages were computed for each participant in each experimental condition, and data re-referenced to the average of channels (see Fig. 1 for grand-averages). Based on visual inspection of the grand average and on previous literature (Mercure et al., 2008), a montage of electrodes was created where the P1 and N170 components were maximal in the right and left occipitotemporal regions (left: 57, 58, 59, 60, 63, 64, 65, 66, 67, 69, 70, 71, 72, 74, 75; right: 77, 78, 83, 84, 85, 86, 89, 90, 91, 92, 95, 96, 97, 100, 101). Based on visual inspection of the individual data, the time windows were defined as follows: P1 (111–179 ms), N170 (155–255 ms). The component peak amplitude within this time window was extracted for each participant, in each condition, for the average of all channels in the left and in the right hemisphere montages.

4. Results

4.1. Behavioral data

Error rates were on average 2.9% for faces and 2.3% for words, which did not differ significantly [$t(24) = 0.80$; $p = 0.432$]. Response times were longer for faces (859 ms) than for words (825 ms) [$t(24) = 2.07$; $p = 0.050$], which was the only significant effect found for behavioral data.

² This uniformity in face gender and ethnic origin aimed to increase the similarity of the faces and to prevent the use of strategies based on skin tone or external features in the one-back task.

³ Development of the MacBrain Face Stimulus Set was overseen by Nim Tottenham and supported by the John D. and Catherine T. MacArthur Foundation Research Network on Early Experience and Brain Development. Please contact Nim Tottenham at tott0006@tc.umn.edu for more information concerning the stimulus set.

¹ TOWRE is a 1-min test that assesses the ability to pronounce printed words accurately and fluently. The child is presented with a list of 104 words and asked to read as many words as possible in 45 s.

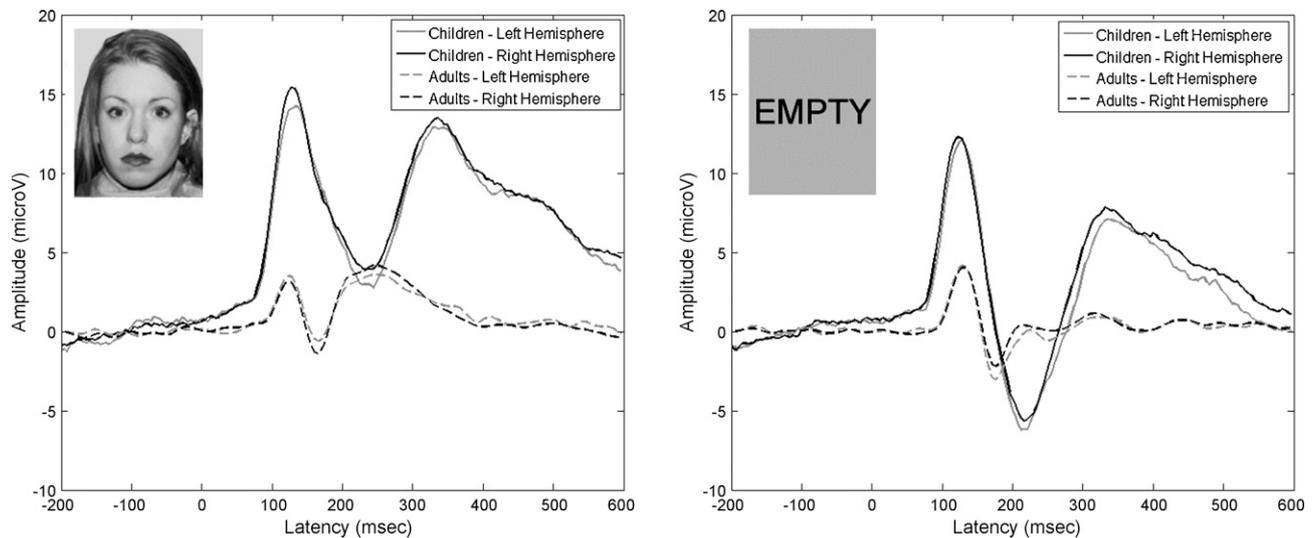


Fig. 1. Grand average waveforms for faces and words, in school-age boys and in adults. Adult data was adapted from [Mercure et al. \(2007\)](#) for illustration purposes.

4.2. ERP data

A repeated measure ANOVA was performed on the peak amplitude of the P1 component for the factors Stimulus Category (Faces, Words) and Hemisphere (Left, Right). Only the stimulus category influenced the P1 peak amplitude, confirming what was visually obvious: faces elicited a larger P1 than words ($F(1, 25) = 27.1$; $p < 0.001$). The same ANOVA on the N170 amplitude also revealed a significant influence of the stimulus category, with a larger N170 for words than for faces ($F(1, 25) = 206$; $p < 0.001$). The Stimulus Category \times Hemisphere interaction was non-significant ($F(1, 25) = 0.2$; $p = 0.679$), suggesting that the robust differential lateralization observed in adults was not present in school-age boys. Since there were P1 differences, a P1 to N170 peak-to-peak difference was computed. This deflection was larger for words than for faces

($F(1, 25) = 55.7$; $p < 0.001$), but the Stimulus Category \times Hemisphere interaction was not significant ($F(1, 25) = 0.6$; $p = 0.428$). When handedness was included as a covariate in these analyses, the same significant and non-significant effects were observed, except that the main effect of Category failed to reach significance on the P1 amplitude and on the P1–N170 peak-to-peak difference. Crucially, the Category \times Hemisphere interaction was non-significant on both the amplitude of the N170 and on the P1–N170 peak-to-peak difference, no matter if handedness was included as a covariate or not. This suggests that the absence of differential lateralization for faces and words is not the result of the inclusion of a few left-handers in the sample.

Lateralization of the N170, calculated as a difference in microvolts between the N170 in the right hemisphere and the N170 in the left hemisphere, did not clearly differ between words and faces, but

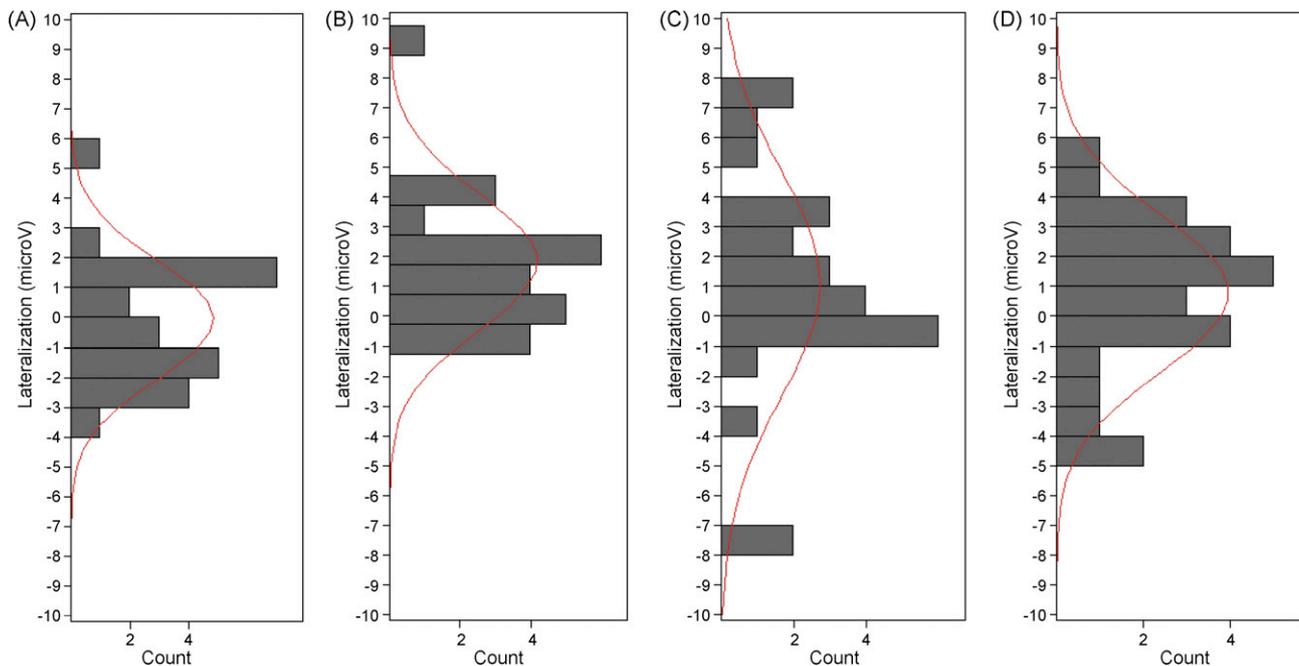


Fig. 2. Distribution of lateralization for (A) faces in adults; (B) words in adults; (C) faces in children; (D) words in children. In this frequency histogram, lateralization of the N170 was calculated as a difference in microvolts between the N170 in the right hemisphere and the N170 in the left hemisphere for each individual. On this lateralization scale, a positive number represents a left lateralized N170, while a negative number represents a right lateralized N170. These graphs suggest that in adults, lateralization differs between faces and words, whereas the children lateralization is more variable and does not clearly differ between stimulus categories. Adult data was adapted from [Mercure et al. \(2007\)](#) for illustration purposes.

Table 1
Correlation matrix showing relations between variables.

	Lateralization faces	Lateralization words	FT	TOWRE	Verbal IQ	Performance IQ
Lateralization faces		$r = 0.49; p = 0.010$	$r = -0.04; p = 0.850$	$r = 0.36; p = 0.074$	$r = 0.44; p = 0.024$	$r = 0.52; p = 0.006$
Lateralization words	$r = 0.49; p = 0.010$		$r = -0.25; p = 0.219$	$r = 0.14; p = 0.455$	$r = 0.44; p = 0.024$	$r = 0.54; p = 0.004$
FT	$r = -0.04; p = 0.850$	$r = -0.25; p = 0.219$		$r = -0.13; p = 0.528$	$r = 0.06; p = 0.776$	$r < 0.01; p = 0.993$
TOWRE	$r = 0.36; p = 0.074$	$r = 0.14; p = 0.455$	$r = -0.13; p = 0.528$		$r = 0.20; p = 0.328$	$r = 0.11; p = 0.589$
Verbal IQ	$r = 0.44; p = 0.024$	$r = 0.44; p = 0.024$	$r = 0.06; p = 0.776$	$r = 0.20; p = 0.328$		$r = 0.80; p < 0.001$
Performance IQ	$r = 0.52; p = 0.006$	$r = 0.54; p = 0.004$	$r < 0.01; p = 0.993$	$r = 0.11; p = 0.589$	$r = 0.80; p < 0.001$	

was extremely variable between individuals (see Fig. 2). All predictors (FT, TOWRE, Verbal IQ, and Performance IQ), as well as the degree of lateralization for faces and for words, were put in a correlation matrix to assess the covariation between these variables (see Table 1 for r and p values). The results were also confirmed by nonparametric correlation (Spearman's rho). A high correlation was found between the two IQ scores, which is not surprising in a group of typical children. More interestingly, N170 lateralization for words correlated with N170 lateralization for faces, and Verbal and Performance IQ scores correlated with N170 lateralization for words and faces. FT level and TOWRE score did not correlate with the degree of lateralization for words or for faces.

To better understand the relation between predictors, a stepwise regression model with an entry criterion of $p < 0.05$ was performed on each stimulus category using these predictors: FT, TOWRE, Verbal IQ and Performance IQ. The results were confirmed by a backward regression model and by robust regression. The same factors were also included/excluded in the model when handedness was entered as a covariate. Performance IQ accounted for a significant amount of variability in lateralization of the N170 for words and for faces (Faces: $F(1, 24) = 9.11, p = 0.006, R^2 = 0.275$; Words: $F(1, 24) = 10.0; p = 0.004, R^2 = 0.295$), in that left lateralization for these stimuli increased with performance IQ. Because the two IQ scores were highly correlated, multicollinearity probably prevented the inclusion of Verbal IQ as a predictor of lateralization (Howitt & Cramer, 2003). When only Verbal IQ was entered in the model a significant amount of the individual variability was accounted for (Faces: $F(1, 24) = 5.8, p = 0.023, R^2 = 0.195$; Words: $F(1, 24) = 5.8; p = 0.024, R^2 = 0.195$). FT and TOWRE scores did not account for statistically significant variability in lateralization for faces and words.

5. Discussion

In the present study, school-age boys performed the same one-back task with the same stimuli as adults reported in a previous study (Mercure et al., 2007, 2008). School-age boys did not show a significant difference in lateralization of their N170 between words and faces. This differential pattern of lateralization was found robustly in adults with the same procedure and stimuli (Mercure et al., 2008), as well as with a similar procedure and stimuli (Joyce & Rossion, 2005; Rossion et al., 2003). This suggests that the adult pattern of lateralization emerges with years of experience of these stimulus categories or with late childhood maturation. It is also congruent with fMRI data showing an age- or skill-related decrease in the activity of several right hemisphere areas in reading (Pugh et al., 2005).

The primary aim of this experiment was to study the factors that account for individual variability in lateralization. More specifically, we assessed the potential role of FT as a prenatal factor biasing the development of lateralization and the potential role of reading skill and Verbal IQ score as factors predicting left lateralization for words in childhood.

In the present study, no correlation was observed between FT level measured by amniocentesis and the degree of lateralization of the N170 in school-age boys. There are a few possible explanations for this result; the first of which is the possibility that FT does not

influence lateralization of cognitive functions. Indeed, the evidence presented in the literature is somewhat contradictory regarding this hypothesis (Bryden et al., 1994; Cohen-Bendahan et al., 2004; Geschwind & Behan, 1982, 1984; Grimshaw et al., 1995; Helleday et al., 1994; Kelso et al., 2000; Mathews et al., 2004; Witelson & Nowakowski, 1991). It could also be argued that the FT level measured from the amniotic fluid did not relate to the fetal blood level during a critical period of brain development. However, children from the same cohort participated in other studies and significant correlations were observed between their FT level and different aspects of behavior and cognition (Baron-Cohen et al., 2004). If the measure taken in the amniotic fluid was not representative of the fetal level, or if it was taken outside critical periods, this measure could not have influenced measures of behavior and cognition. It is therefore possible that the influence of FT on behavior and cognition is mediated by an influence of the androgen hormone on aspects of brain development other than lateralization. Indeed, there is evidence of gender differences in several brain structures, for example in the hypothalamus, amygdala, corpus callosum, thickness of the cortex, sylvian fissure and planum temporale (Baron-Cohen et al., 2004). Further brain imaging is underway to evaluate these possibilities (Ashwin, 2009).

Another possible explanation for the present results is that the impact of testosterone on lateralization appears later in development. As was previously discussed, the boys who participated in this study did not show a differential pattern of ERP lateralization for words and faces when considered as a group. Developmental data from other ERP studies indicates that N170 lateralization reliably appears in teenage years (Taylor et al., 2004). It is therefore possible that the level of testosterone in a critical period of fetal development influences the way this pattern appears in teenage years. It will be possible to test this hypothesis when the boys of this cohort become teenagers. Alternatively, it is possible that a link between lateralization and FT exists in school-age boys, but that the present sample size prevented the appearance of significant results. If such a relationship existed, its effect is much smaller than that of other factors found with the same sample in the present study.

The second aim of this study was to test the hypothesis that reading skill or Verbal IQ would be associated with left lateralization for words. No correlation was found between the TOWRE score and the degree of lateralization for words in school-age boys, a result that could be attributed to the lack of variability in reading scores. Indeed, most children were better readers than average, and only two children scored slightly below average. The predicted correlation between Verbal IQ and left lateralization for words was observed. However, both Verbal and Performance IQ scores correlated with left lateralization of the N170 for both stimulus categories, suggesting that the relation was not specific to language abilities and language lateralization. An interesting result from this experiment is the strong positive correlation that was observed between left lateralization for words and left lateralization for faces in school-age boys. The same correlation was also found in a mixed-gender group of adults (Mercure et al., 2007). Adults and school-age boys who had a very left lateralized N170 for words also tended to have a left lateralized N170 for faces. This general lateralization bias correlated with both IQ scores in school-age boys, but it is

unclear if this correlation between lateralization and IQ also existed in adults given that the IQ scores were not collected in this sample. The fact that this correlation between lateralization and IQ was independent of the stimulus category and of the IQ scale suggests that the explanation probably lies in a domain-general cognitive processing that contributes to different tasks and stimuli. It is possible that left lateralization of the N170 is correlated with better attention or working memory, which could influence both Verbal and Performance IQ scores. However, the present data should not be interpreted as an indication that higher IQ, better attention, or better working memory increases left lateralization. These correlations suggest a statistical association between IQ scores and N170 lateralization. The direction of the causality might be one way or the other, or may well be reciprocal. Further research is required to better understand the link between IQ and lateralization. Nevertheless, this finding suggests the importance of controlling for general IQ scores when studying the relation between a specific skill and lateralization. Since many reading tests correlate with Verbal IQ, a correlation between left lateralization for written words and reading skills could potentially be explained by the association of left lateralization with more general cognitive abilities such as attention or working memory.

The finding of a general lateralization bias conflicts with what would be predicted by the callosal hypothesis. In this hypothesis, lateralization of cognitive functions is thought to result from the disconnection of the hemispheres by pruning of callosal cells. According to this mechanism, some individuals may be more lateralized than others and a strong left lateralization for words should correlate with a strong *right* lateralization for faces. The GBG model better accommodates the finding of a positive correlation between lateralization for faces and for words, which was found in school-age boys in the present study, as well as in a mixed-gender group of adults (Mercure et al., 2007). Indeed, according to this hypothesis, lateralization results from differences in the developmental rates of the hemispheres. This development could affect many different cognitive functions, and could therefore give rise to a positive correlation in their lateralization.

To conclude, this study revealed that the development of differential lateralization for words and for faces extends into late childhood, but there was no evidence for a role of FT levels on this developmental pattern in school-age boys. Lateralization across domains appeared to be related at the individual level in the form of a general lateralization bias predicted by IQ scores. Further studies are required to clarify the cognitive mechanisms that underlie this general lateralization bias, as well as the roles of maturation and experience in the development of functional lateralization.

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