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How reading acquisition changes children's spoken language network

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ABSTRACT

To examine the influence of age and reading proficiency on the development of the spoken language network, we tested 6- and 9-years-old children listening to native and foreign sentences in a slow event-related fMRI paradigm. We observed a stable organization of the peri-sylvian areas during this time period with a left dominance in the superior temporal sulcus and inferior frontal region. A year of reading instruction was nevertheless sufficient to increase activation in regions involved in phonological representations (posterior superior temporal region) and sentence integration (temporal pole and pars orbitalis). A top-down activation of the left inferior temporal cortex surrounding the visual word form area, was also observed but only in 9 year-olds (3 years of reading practice) listening to their native language. These results emphasize how a successful cultural practice, reading, slots in the biological constraints of the innate spoken language network.

1. Introduction

Language in humans has both early and protracted development. From birth onward, infants show complex language capacities and begin to learn their native language (Dehaene-Lambertz, Hertz-Pannier, & Dubois, 2006; Kuhl, 2004). These early capacities rely on a set of perisylvian brain regions, close to what has been described in adults (Dehaene-Lambertz, Dehaene, & Hertz-Pannier, 2002). In particular, a left dominance for language processing is observed at the level of the *planum temporale* already during the first months of life (Dehaene-Lambertz et al., 2010; Pena et al., 2003) and even before term (Mahmoudzadeh et al., 2013); and activation in the left inferior frontal region is detected when infants are engaged in a short-term verbal memory task (Dehaene-Lambertz, Hertz-Pannier, Dubois et al., 2006).

Although the main rules of human verbal communication are acquired within the first three years of life (Bernal, 2001; Gertner & Fisher, 2012; Mills, Coffey-Corina, & Neville, 1993), children continue to improve their language expertise until adulthood, increasing their vocabulary and their syntactic skills. Several functional magnetic resonance imaging (fMRI) studies report that activation increases correlate with age in several regions of the perisylvian network (Brauer & Friederici, 2007; Lidzba, Schwilling, Grodd, Krageloh-Mann, & Wilke, 2011; Schmithorst, Holland, & Plante, 2006; Szaflarski, Holland, Schmithorst, & Byars, 2006; Szaflarski et al., 2012). These sustained changes can be explained by the heterogeneous calendar of myelination and of synaptogenesis/pruning in the different perisylvian areas, spread over several years (Paus et al., 1999; Sowell et al., 2003; Yakovlev & Lecours, 1967) and by an increased mastery of spoken language, but another cultural factor, rarely marked out in studies of normal language development might also affect neural responses in this network: reading. Especially in the case of alphabetic writing, readers develop better metaphonological capacities and short-term verbal memory than those who are illiterate (Morais & Kolinsky, 2005). Their speech perception becomes influenced by orthography (Ventura, Morais, Pattamadilok, & Kolinsky, 2004; Ziegler & Ferrand, 1998) and they better retained the meaning of new words when they are exposed to their orthography, even incidentally (Ricketts, Bishop, & Nation, 2009). They also have access to more complex syntactical structures and can acquire a richer and more diverse vocabulary through books. Thus reading has an unquestionable influence on oral language processing, and certainly plays a role in the neural changes observed during childhood.

Comparisons of the neural bases of spoken language between literate and illiterate adults have revealed higher activations in the left parieto-temporal region and involvement of supplementary regions, such as the visual word form area (VWFA) in tasks involving spoken language (Carreiras et al., 2009; Castro-Caldas, Petersson, Reis, Stone-Elander, & Ingvar, 1998; Dehaene et al., 2010; Li et al., 2006). Similar differences have been obtained when

Abbreviations: VWFA, visual word form area; STS, superior temporal sulcus.

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comparing normal adult readers and dyslexics (Blomert, 2011; Paulesu et al., 2001). Similarly normal child readers have larger activation in the left posterior temporal region than impaired readers and recruit the VWFA, when performing auditory spelling and rhyming tasks (Booth et al., 2004; Desroches et al., 2010), as well as when merely listening to their native language (Monzalvo, Fluss, Billard, Dehaene, & Dehaene-Lambertz, 2012).

Our goal was thus to study the early impact of reading on the spoken language network using fMRI. We used a slow event-related design to test normal 6-and 9-year-old children listening to short sentences in their native language and a foreign language (one sentence every 12 s, repeated once). The subtraction of the responses to the foreign sentences from the native sentences aimed at disentangling specific linguistic effects from the general effects of age and education on the auditory system whereas sentence repetition aimed at parceling the superior temporal regions. Stimulus repetition has been used to separate different regions depending on the temporal decay of mental representations computed from the stimulus (Henson, Shallice, & Dolan, 2000). In adults, when the same sentence is repeated 14.4s later, the superior temporal sulcus, which hosts abstract linguistic representations (Davis & Johnsrude, 2003; Pallier, Devauchelle, & Dehaene, 2011), but not the upper regions in the superior temporal gyrus, displayed a decrease of amplitude of the BOLD response (Dehaene-Lambertz, Dehaene et al., 2006). In infants, a similar repetition effect was observed but only when the sentence was immediately repeated (Dehaene-Lambertz et al., 2010) and not when the same delay than in adults was used (Dehaene-Lambertz, Dehaene et al., 2006). Working memory and sentence intelligibility are crucial factors in the lengthening of the temporal delay. Reading notably improves working memory, thanks to a better phonological loop. We have thus examined whether the neural impact of reading goes beyond the early stages of phonological coding and change the whole sentence integration in the superior temporal sulcus facilitating a repetition suppression effect.

The effects of age and education are difficult to separate, as the academic curriculum is generally homogeneous in a given country, especially for fundamental acquisitions such as reading. Thus older children following a normal curriculum are by default more expert readers than younger children. We thus specifically examined the impact of reading in our 6-year-olds by taking advantage of the gap between the academic and the civil year. We set up two groups of approximately the same age but with a one-year difference in reading instruction. This comparison aimed to examine whether reading quickly modifies the spoken language system from the first year of teaching onward. In particular, we wondered whether the changes in the posterior temporal region for native sentences and the recruitment of the VWFA, described in the studies that compared literate and illiterate adults, would already be visible after a few months of reading practice.

2. Methods

2.1. Subjects

Forty-nine children, 25 boys and 24 girls, were recruited in the Paris area and divided into two groups based on age (6- and 9-year-old children) or three groups based on reading abilities (pre-readers, beginners and advanced readers). All parents and children gave their written consent. The study was approved by the local ethical committee for biomedical research.

Children with cognitive, neurological or behavioural disorders, hearing deficit, not corrected visual problem and mental retardation were excluded from the study. At the time of the study, we checked with the parents and teacher that the child was following a normal academic curriculum without difficulties. We confirmed his/her normal intellectual development with two subtests of the WISC (the block design and the similarities subtests). If a child performed poorly (scaled score below 8 corresponding to percentile rank of 25) in one of these subtests (usually because of shyness at the beginning of the test), he/she was also tested with the picture completion and the vocabulary subtests. We also examined their handedness, verbal memory, verbal and reading abilities (Table 1).

The oldest group or advanced readers (23 children, 9 years, 7 months ± 6 months) had three complete years of reading experience. Eleven children in this group came from a low socio-economical background (SES) and among them 7 were bilingual (only one spoke a romance language, i.e. Romanian). These 7 children were from migrant families (Pakistan, Mali, Algeria, Yugoslavia and Romania), but all, except one, were born in France. They were all following the normal French academic curriculum since kindergarten (i.e. around 6 years in a French teaching environment). According to the parents who filled a questionnaire on cultural habits, their children showed a marked preference to speak French even at home suggesting that French was probably their dominant language. Their fluency in French was confirmed by their normal performances in our French verbal and reading tests. In a previous published paper focused on this question (Monzalvo et al., 2012), we analyzed the effects of SES in these same 23 children. Our low-SES children had lower verbal and reading performances than their higher SES peers as noted in numerous studies (Hackman & Farah, 2009; Noble, McCandliss, & Farah, 2007), but they all remained in the normal range (see complete results in Monzalvo et al., 2012, and in Table 1 here). No significant functional difference related to SES/bilingualism was observed in the brain responses to speech at the group level. This result is congruent with studies in adults showing only weak differences, if any, between monolinguals and proficient bilinguals in MRI activations during speech listening (Abutalebi, 2008). Therefore, we merge here these two groups to increase our statistical power to detect differences between ages and to have a better coverage of the normal range of oral and written language capacities.

None of the 6-year-old children was coming from low-SES family and only one was bilingual. This child was fluent in French and German, performing above average in all French verbal and reading tests. For the 6-year-olds, we tried to recruit children of approximately the same age but with one year of difference in reading instruction by taking advantage of the gap between the civil and academic years. We thus divided the 6-year-olds into two groups: 13 children in kindergarten with no reading instruction, called "pre-readers" (6 boys, 7 girls; mean age: 6 years 2 months, 70–80 months) and 13 children tested at the end of the first grade year, called "beginners" (7 boys, 6 girls; mean age: 6 years 10 months, 70–87 months). Children in this group were tested 8–16 months (mean = 11 months) after their entrance in first grade. However, despite an overlap between the two groups, a significant age difference remained. As expected, the number of words read in 1 min (Khomsi, 1999) was significantly lower in the pre-readers relative to the beginners (4 [0–10] vs. 40 [22–54] w/mn, $p < .001$). This test is a standardized list of 105 words with increased difficulties. The first 15 words are monosyllabic and frequent, and comprise articles (e.g. "le"), pronouns (e.g. "il") or simple open-class words (e.g. "nu"). All pre-readers were able to read and write their first name. Some of them were also able to read the first words of this list but 9 on 13 were reading less than 5 words in 1 min, and the remaining 4 children, between 5 and 10. The reading performance within the 6-year-old group was correlated with age ($R^2 = 0.48$, $F(1,24) = 24$, $p < .001$). When the effect of age was discarded by using the residuals of the linear regression between age and the number of words read by minute, a significant difference was still observed