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Developmental patterns of expressive language hemispheric lateralization in children, adolescents and adults using functional near-infrared spectroscopy

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ABSTRACT

The development of language hemispheric specialization is not well understood in young children, especially regarding expressive language functions. In this study, we investigated age-related changes in expressive language lateralization patterns in a population of children (3–6 and 7–10 years old), adolescents (11–16 years old), and young adults (19–30 years old). During functional near-infrared spectroscopy recordings, all participants performed a verbal fluency task, which consisted in naming as many words as possible belonging to a given semantic category. Hemoglobin concentration changes were measured in bilateral frontal and temporal cortical areas. During the language task, results showed a strong left hemisphere response along with weaker right hemisphere activation in all groups. Age-related increases in hemodynamic responses were found bilaterally, with younger children showing smaller hemodynamic responses than adolescents and adults in both hemispheres. Overall, these findings confirm that a left hemisphere specialization is already established in young children and persists through adulthood. Early left hemisphere specialization for expressive language suggests that language development hinges on structural and functional properties of the human brain with little reorganization occurring with development.

1. Introduction

It is now well recognized that language functions are associated with structural and functional hemispheric differences in adults (Cai et al., 2013; Hugdahl and Westerhausen, 2009; Knecht et al., 2000; Mazoyer et al., 1993). Geschwind and Levitsky (1968) were among the first to suggest a left structural asymmetry and reported a longer left *planum temporale* in a majority of the post-mortem brains they studied compared to the homologous area in the right hemisphere. Their findings supported the works of Pierre Broca in 1861 who observed left fronto-temporal lesions in aphasic patients, suggesting a left hemisphere functional dominance for language (Broca, 1861). Since then, anatomical asymmetries have been documented in infant and fetus brains, suggesting that hemispheric differentiation is already present at birth (Chi et al. 1977; Glasel et al., 2011; Wada et al. 1975).

Several neuroimaging and neuropsychological studies have also associated language processing with functional asymmetries within left frontal and temporal regions in healthy individuals and in various clinical populations (Belin et al. 2000, 2002; Binder et al. 1996; Dorsaint-Pierre et al., 2006; Gallagher et al., 2008a,2008b; Gallagher et al., 2012; Knecht et al., 2000; Springer et al., 1999; Szaflarski et al., 2006, 2012; Vannest, Karunanayaka, Schmithorst, Szaflarski, & Holland, 2009; Zatorre, 1989). However, little is known about the development of language hemispheric specialization throughout childhood and adolescence, especially regarding expressive language functions. Indeed, research in this domain remains sparse and it is still unclear whether language maturation relies on inborn functional properties within the left hemisphere or if functional hemispheric specialization matures with

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experience and exposure to a given language (Dehaene-Lambertz et al., 2006).

Regarding receptive language function, studies using various brain imaging techniques in typically developing individuals have supported a left lateralization for speech-sounds processing already present at birth (Beauchemin et al., 2011; Peña et al., 2003) or in the first months of life (Bortfeld et al. 2009, 2007; Dehaene-Lambertz et al., 2002; Dehaene-Lambertz, 1997; Kuhl et al., 2006). Other evidence from electroencephalography recordings suggested that the temporal lobe contains specific neural circuits for phoneme discrimination (Cheour et al., 1998). More recently, it has been found that newborns discriminate between the vowel /a/ spoken by the mother's voice and spoken by a female stranger's voice: a left temporal activation was found for the mother's voice and a right temporal activation for the stranger's (Beauchemin et al., 2011). These results were interpreted as indicative of a phonemic discrimination in the mother's voice only, supporting functional left lateralization at a very young age for receptive language abilities.

In contrast, studies investigating expressive language functions in children have produced controversial results. Some suggest that left hemispheric specialization is probably not well established in young children and continues to increase with age, possibly into early adulthood (Berl et al., 2014; Everts et al., 2009; Gaillard et al., 2000; Holland et al., 2001, 2007; Lidzba et al. 2011; Ressel et al. 2008; Szaflarski et al. 2006). For instance, Holland et al. (2001) found a significant relationship between hemispheric specialization of language functions and age in children aged 7–18 years who completed a verbal fluency task during an fMRI recording. These authors showed increasing degrees of left hemisphere dominance with age. In another study, they also found correlations between degrees of left hemisphere lateralization for language functions and age, but also showed that the lateralization pattern varies depending on the task (Holland et al., 2007). Specifically, the authors presented their subjects, aged between 5 and 18 years, with four language tasks involving different cognitive processes (verb generation, story processing, syntactic prosody and word-picture matching tasks) to evaluate age-related changes in lateralization according to each paradigm. Results showed that age-related changes in lateralization patterns in healthy children were stronger and cerebral activations were more left lateralized during a verb generation task than during the other three tasks. In addition, the greatest changes were observed in the inferior frontal gyrus and dorsolateral prefrontal regions. These results support earlier work by Wood et al. (2004) showing that the degree of lateralization changes with age might be task-dependent. Specifically, the authors examined children, adolescents and adults while they performed a verb generation task and a verbal fluency task (lexical retrieval) during an fMRI scan. Most children showed left-lateralized activation patterns, but the strength of hemispheric dominance increased with age only in the case of the verb generation task. Others, however, have documented similar language representations in children aged between 7 and 14 years and adults using a verbal fluency task, suggesting that language lateralization patterns related to expressive language are already established by age 7 (Gaillard et al., 2003). Likewise, using a picture naming task in a MEG study, Sowman et al. (2014) found significant left lateralization in 24 preschool-aged children aged 3–6 years, suggesting that cerebral regions responsible for language production are already left lateralized at this young age. Moreover, in a recent study by Cai et al. (2013), the authors examined a group of left-handed participants with atypical right hemispheric speech dominance and found that they were all also atypically left hemispheric dominant for spatial attention. This result supports the innate origin hypothesis of language lateralization since there is little probability that the opposite asymmetry of both functions in all their participants could be due to independent lateralization rather than to a common origin.

Overall, controversy still exists for expressive language lateralization representation in children, adolescents and adults. Divergent conclusions regarding the maturation of expressive language dominance may stem from methodological differences regarding sample age ranges and language tasks in these studies. To our knowledge, there is no study investigating expressive language development covering both an extensive age range and an early stage of expressive language development using the same task across ages. In addition, another major limitation stems from difficulties in assessing expressive language functions in young children, mainly because of movement restrictions and difficulty in assessing task performance during data acquisition. For instance, various neuroimaging techniques, including fMRI (Gaillard et al., 2000; Holland et al., 2001, 2007; Szaflarski et al., 2006) and magnetoencephalography (MEG) (Kadis et al., 2011; Ressel et al., 2008; Sowman et al. 2014), have been employed to examine the developmental dynamics of expressive language. Alternately, functional near-infrared spectroscopy (fNIRS) is a non-invasive, functional imaging technique that has no major restrictions on movements or verbalization during recording, which renders the technique suitable for investigations in young children (Wilcox et al., 2005). This technique is based on the light absorption properties of oxyhemoglobin (HbO), deoxyhemoglobin (HbR) and total hemoglobin (HbT) concentrations within the near-infrared spectrum, allowing for measurement of hemodynamic changes related to cerebral activity (Boas et al., 2004; Gratton et al., 1997; Gratton and Fabiani, 2007; Strangman et al., 2002; Watanabe et al., 1998). In the past few years, our research group has successfully used fNIRS for the assessment of expressive and receptive language abilities in healthy adults (Paquette et al., 2010) and children (Gallagher et al., 2007), epileptic patients (Gallagher et al., 2008a,2008b), and healthy adults performing a reading aloud task (Safi et al., 2012). However, NIRS studies investigating left and right hemispheric specialization in young children have mainly used receptive language paradigms in contrast with expressive language development (for recent reviews, see Homae (2014) and Rossi et al. (2012)).

Given the methodological differences between previous studies and the limitations regarding the assessment of children performance in a scanner, the present study aimed to characterize the maturation patterns of hemispheric specialization for expressive language functions in a sample covering different developmental stages of development (3 years old to adulthood), using the same expressive language task (verbal fluency) across ages. In order to accurately evaluate expressive language development across all ages, we used fNIRS, which allows subjects to speak overtly due to its relatively good tolerance to movement and thus allows monitoring of the child's performance. This task was used by our team in several previous studies (Gallagher et al., 2007, 2008a, 2008b) and was shown to reflect vocabulary knowledge that starts to develop in preschool years and continues to grow through adulthood. It was chosen based on studies by Holland et al. (2001, 2007) and Wood et al. (2004), who showed that age related-changes in lateralization varies depending on the task, with the greatest age changes identified using this task. Thus, it was hypothesized that if language specialization establishes itself early in childhood, left brain areas devoted to expressive language processing (Broca's area) should be activated in young children and little reorganization should occur with development. In contrast, if cerebral language dominance is developed with experience and exposure to language, a more bilateral activation pattern should be observed early in development with a gradual left hemisphere specialization with age.