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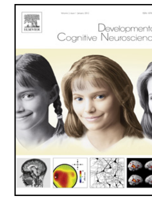

Word and object recognition during reading acquisition: MEG evidence

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ABSTRACT

Studies on adults suggest that reading-induced brain changes might not be limited to linguistic processes. It is still unclear whether these results can be generalized to reading development. The present study shows to which extent neural responses to verbal and nonverbal stimuli are reorganized while children learn to read. MEG data of thirty Basque children (4–8y) were collected while they were presented with written words, spoken words and visual objects. The evoked fields elicited by the experimental stimuli were compared to their scrambled counterparts. Visual words elicited left posterior (200–300 ms) and temporal activations (400–800 ms). The size of these effects increased as reading performance improved, suggesting a reorganization of children's visual word responses. Spoken words elicited greater left temporal responses relative to scrambles (300–700 ms). No evidence for the influence of reading expertise was observed. Brain responses to objects were greater than to scrambles in bilateral posterior regions (200–500 ms). There was a greater left hemisphere involvement as reading errors decreased, suggesting a strengthened verbal decoding of visual configurations with reading acquisition. The present results reveal that learning to read not only influences written word processing, but also affects visual object recognition, suggesting a non-language specific impact of reading on children's neural mechanisms.

1. Introduction

Literacy is a relatively recent human invention that implies structural brain changes and a wide reorganization of different brain functions (Carreiras et al., 2009; Dehaene, 2011; Dehaene et al., 2015). It requires the acquisition of new linguistic abilities (e.g., letter-sound association, linguistic decoding of visual configurations), as well as the refinement of nonverbal visual skills (e.g., fine-grained visual object recognition). However, it is still unclear how these linguistic and non-linguistic changes can support reading acquisition and what is their relative contribution during reading development. Recent theoretical models assume that during the first stages of reading development new audio-visual objects need to be created and stored. Hence, changes in phonological processing are considered a primary requirement to reliably learn and memorize new visual objects (i.e, letters and words; Blomert, 2011). On the other hand, a different theoretical perspective mainly emphasizes the specific role of the visual domain and describes reading acquisition as a visual perceptual learning, which requires an early reorganization of the brain's ventral stream (Dehaene et al., 2015; Kolinsky et al., 2011; Reis et al., 2006; Ventura et al., 2013). Unfortunately, most of the evidence so far collected on this topic comes from studies in adult participants. These findings cannot be easily generalized to children learning to read and they cannot directly inform us about the developmental trajectories of different reading-related brain changes during reading acquisition in childhood.

The present MEG study will specifically investigate verbal and nonverbal changes while children learn to read. Specifically, the aim of the experiment is twofold: 1) providing a temporal and spatial description of how reading acquisition affects children's linguistic mechanisms in the auditory and visual modality; 2) testing whether and how children's visual object recognition is affected by learning to read.

Most of what we know about brain areas involved in reading processing comes from studies on adults (Bolger et al., 2005; Jobard et al., 2003), which showed that written words activate the left language network in skilled readers (Dehaene et al., 2010;

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Dehaene, 2011; Simos et al., 1998). When literates were presented with visual verbal stimuli, greater activations in the left occipitotemporal sulcus (visual word form area, Dehaene et al., 2010; Pinel et al., 2015) and in left frontotemporal regions (Carreiras et al., 2009; Dehaene et al., 2010) were observed compared to illiterates or less skilled readers. Modular models assume that the visual word form area is responsible for orthographic encoding at a first reading stage (McCandliss et al., 2003), while the left frontotemporal activity would reflect later processes of phonological, lexical and semantic encoding (Blomert, 2011; Jobard et al., 2003; Salmelin et al., 2000). Interactive models claim that frontal brain areas can influence the activity of the visual word form area even at early stages of reading. In this case the visual word form area is considered a multimodal integration hub, which receives top-down modulations from more anterior areas (Price and Devlin, 2011; for a discussion on different models of word recognition see Carreiras et al., 2014). Magnetoencephalographic (MEG) and electroencephalographic (EEG) data provided a contrastive pattern of results, with some studies showing brain responses in left occipitotemporal areas between 100 and 300 ms after stimulus onset (Bentin et al., 1999; Cohen et al., 2000; Helenius et al., 1999; Simos et al., 1998) followed by left temporal activity approximately 200 ms after stimulus onset (Carreiras et al., 2015; Simos et al., 1998, 1999; for a review see Salmelin et al., 2000), and some others showing frontal activations even before 200 ms (Cornelissen et al., 2009; Woodhead et al., 2014). Those two brain responses (i.e., frontotemporal and occipitotemporal) increase as reading performance improves (Dehaene et al., 2010; Pegado et al., 2014; Pinel et al., 2015) and quick reading-induced changes can be observed even after few training sessions (Hashimoto and Sakai, 2004; Song et al., 2010; Yoncheva et al., 2010; Xue et al., 2006).

Studies on children's reading acquisition also suggest a quick reorganization of brain networks. However, different results have been reported depending on the paradigm and the amount of reading instruction examined (see Table 1). Neuroimaging studies using longitudinal and cross-sectional designs showed changes in left occipitotemporal areas (Ben-Shachar et al., 2011; Brem et al., 2010; Pugh et al., 2013). Cross-sectional studies also showed changes in frontotemporal areas (Pugh et al., 2013; Turkeltaub et al., 2003), whose localizations were highly similar to those of adults (Houdé et al., 2010; Martin et al., 2015). Variations in occipitotemporal activity were observed after few training sessions (Brem et al., 2010), with an increased engagement of posterior occipitotemporal areas as reading performance improves (Shaywitz et al., 2002; for a metanalysis see Martin et al., 2015). Modulations in left frontotemporal responses were mainly observed in cross-sectional studies that considered a wider period of formal instruction (Pugh et al., 2013; Turkeltaub et al., 2003). Few electrophysiological studies are so far available and they mainly focused on short periods of reading instruction (from few hours to one year). They adopted a longitudinal design and reported changes in occipital brain responses with reading training (Brem et al., 2010; Maurer et al., 2006). These brain responses appeared later in time as compared to adults (later than 200 ms after stimulus onset, Maurer et al., 2006; see also Maurer et al., 2005) and were more bilaterally distributed (Brem et al., 2010; Maurer et al., 2006).

The present MEG study will examine a group of children who received different amounts of reading instruction (up to two years) in order to test whether and when occipital and temporal brain activity changes can be observed in developmental reading processes.

Literacy does not seem to induce changes only in processing of written verbal material, but also in speech processing. Neuroimaging studies on adult readers showed that auditory verbal stimuli usually elicit greater left parieto-temporal activity (i.e., planum temporale) relative to illiterates, especially when the task involves repetition or lexical decision (Castro-Caldas et al., 1998; Dehaene et al., 2010; Dehaene, 2011). These areas are supposed to be involved in grapheme-phoneme conversion (Blomert, 2011; Dehaene, 2011) and their activation would increase because the link between phonemic and graphemic representations is strengthened as reading improves (Dehaene et al., 2015; Pattamadilok et al., 2010). Electrophysiological studies provided a temporal characterization of these brain activation changes, showing left temporal sensitivity to spoken words 300 ms after stimulus onset (Helenius et al., 2009; Simos et al., 1998, 1999), which depends on reading performance (Helenius et al., 2009).

Data on literacy and children's speech processing are scarcer and mainly focused on reading disorders. Similarly to adults, skilled young readers listening to speech usually exhibit increased left temporal activations compared to reading-impaired children (Blau et al., 2010; Monzalvo et al., 2012; but see Simos et al., 2000), and these responses correlate with children's reading skills (Monzalvo et al., 2012). Very few studies on speech-related changes during normal reading development have been carried out. In Pugh et al. (2013) a group of children with different degrees of reading performance (5–9 years of age) had to decide whether a picture matched with the following spoken stimulus (a word or a pseudoword). Positive correlations were found between behavioral reading scores and brain responses to spoken targets in the left frontotemporal cortex and precuneus. In Monzalvo and Dehaene-Lambertz (2013) children with different amounts of reading instruction (6–9 years of age) passively listened to spoken sentences in native and foreign language. After few months of reading training, six-year-old children already showed increased activity for the 'native-foreign' contrast in left perisylvian regions. However, there was no difference between nine and six-year-olds in the 'native-foreign' comparison. Also, the overall brain responses to speech (native and foreign sentences) increased with age (similarly to Pugh et al., 2013). Unfortunately, the time sequence of these brain changes is still unclear since no electrophysiological study has so far investigated auditory processing as reading develops.

The present MEG study will provide for the first time a temporal description of reading-induced brain changes in children's speech processing.

Finally, recent findings suggest that effects of reading acquisition would extend beyond the verbal domain (Dehaene et al., 2010, 2015; Dundas et al., 2013; Pegado et al., 2014), influencing visual object processing (Reis et al., 2006). Behavioral studies showed that illiterate adults are usually less accurate than matched literate controls at detecting, recognizing, and naming visual objects (Ardilla et al., 1989; Kolinsky et al., 2011; Kremin et al., 1991; Reis et al., 1994; Szwed et al., 2012; Ventura et al., 2013). These differences are not specific to any object category and they would be the result of formal reading instruction, which represents an intensive perceptual training in detecting, segmenting, recognizing and interpreting visual representations (e.g., letter strings; Kolinsky et al., 1990; Reis et al., 2006). Neuroimaging studies on adults are only partially in line with these behavioral findings. Literate adults show increased occipital responses to visual stimuli compared to illiterates, suggesting an impact of literacy at early automatic stages of visual processing (Dehaene et al., 2015). However, when brain areas specifically associated to visual object recognition were considered (posterior-lateral sides of the fusiform gyrus, Malach et al., 1995) literacy showed a modest impact, with no changes in the peak responses to visual objects and small variations of the cortical boundaries for faces (Dehaene et al., 2010). Similarly, electrophysiological studies reported an enhancement of early posterior responses (140–180 ms) to different object categories (i.e., tools, houses, faces) as reading improves, however, later responses of object discrimination varied only for faces and houses (500 ms; Pegado et al., 2014).