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Effects of lexicality and word frequency on brain activation in dyslexic readers

Stefan Heim [a,b,c,*], Anke Wehnelt [b,c], Marion Grande [b], Walter Huber [b], Katrin Amunts [a,c]

[a] *Section Structural–Functional Brain Mapping, Department of Psychiatry, Psychotherapy, and Psychosomatics, Medical School, RWTH Aachen University, Germany*
[b] *Section Neurological Cognition Research, Department of Neurology, Medical School, RWTH Aachen University, Germany*
[c] *Institute of Neurosciences and Medicine (INM-1), Research Centre Jülich, Jülich, Germany*

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ABSTRACT

We investigated the neural basis of lexical access to written stimuli in adult dyslexics and normal readers via the Lexicality effect (pseudowords > words) and the Frequency effect (low > high frequent words). The participants read aloud German words (with low or high lexical frequency) or pseudowords while being scanned. In both groups, both Lexicality effect and Frequency effect involved Broca's region (areas 44 and 45). Whereas the effects were stronger for dyslexic than normal readers in area 44, area 45 showed the reverse pattern. These findings mimic recent results from an fMRI study on dyslexic primary school children, indicating that lexical access to written stimuli poses increased and enduring difficulties on dyslexic readers, at least in a language with a transparent orthography. Additionally, data from four compensated adult dyslexics are reported and discussed, which hint at the importance of both Broca's and Wernicke's region for recovery from childhood dyslexia.

1. Introduction

Developmental dyslexia is a reading disorder occurring in spite of normal intelligence, adequate educational resources, and the absence of sensory deficits. It represents one of the most common developmental disorders. Five to seventeen percent of the population in the United States was classified as dyslexics (Shaywitz et al., 1998); similarly, the prevalence estimations in Germany range from 3% to 20% (Schulte-Körne & Remschmidt, 2003). A biological basis of dyslexia has been demonstrated both genetically (cf. e.g. Decker & Bender, 1988; DeFries, Fulker, & LaBuda, 1987; Grigorenko, 2001; McManus, 1991; Schulte-Körne, 2001) and with respect to abnormalities in brain morphology (e.g. Kronbichler, Wimmer, Staffen, Hutzler, & Mair Ladurner, 2008; Silani et al., 2005), brain function (e.g. Georgiewa et al., 1999; Shaywitz et al., 2003; Simos, Breier, Fletcher, Bergman, & Papanicoleao, 2000), and both (e.g. Hoeft et al., 2007). Since reading problems, along with phonological processing problems, are the most common symptoms in dyslexia, reading and phonological processing are among the most frequently used tasks in functional neuroimaging studies (e.g. Bolger, Minas, Burman, & Booth, 2008; Booth et al., 2006; Booth, Cho, Burman, & Bitan, 2007; Cao, Bitan, & Booth, 2008; Hoeft et al., 2007; Paulesu et al., 2001; Temple et al., 2001; Wimmer et al., 2010). Such studies consistently identify activation differences in three parts of the brain (although with substantial variability within these regions): left inferior frontal cortex, left temporo-parietal cortex, and left temporo-occipital cortex (e.g. Richlan et al., 2010; Wimmer et al., 2010; for reviews and meta-analyses see Démonet, Taylor, & Chaix, 2004; Richlan, Kronbichler, & Wimmer, 2009, 2011; or Sandak et al., 2004). According to Démonet et al. (2004), there is a functional distinction between these three regions: The occipito-temporal cortex, or "ventral pathway", is assumed to be involved in automatic word-form access; the temporo-parietal cortex, or "dorsal pathway", probably supports slow phonology-based assembly processes such as grapheme-to-phoneme conversion; and the inferior frontal cortex possibly related to phonology and articulation. The quantitative meta-analysis by Richlan et al. (2011) confirms these findings, contributing further to the understanding of their functional significance by demonstrating distinctions between dyslexic children vs. adults, with the former showing deactivation in the temporo-parietal cortex and the adults in the two other regions. According to their findings, occipito-temporal cortex might not only be involved in visual word form processing, but also earlier processing steps. The temporo-parietal cortex is associated with phonological processes, as in the Démonet et al. (2004) paper; however, the authors suggest a functional separation of temporal and parietal areas in order to better account for heterogeneities in the dyslexia literature. Moreover, the authors observed a functional disconnection between posterior superior temporal under activations and inferior frontal activations, which are taken to demonstrate the involvement of these two regions in different types of phonological processing (i.e., receptive vs. productive, respectively).

* Corresponding author at: Department of Psychiatry, Psychotherapy, and Psychosomatics, Medical School, RWTH Aachen University, Pauwelsstrasse 30, 52074 Aachen, Germany. Fax: +49 2461 612820.

E-mail addresses: s.heim@fz-juelich.de, sheim@ukaachen.de (S. Heim).

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Interestingly, it is in particular the temporo-parietal cortex and inferior frontal cortex that seem sensitive to remediation (Gabrieli, 2009) in that previously reduced activation is restored to a normal level. This finding stands somewhat against the recently published "predictive coding" account by Price and Devlin (2011). This account would predict that training-induced activation increase should (at least transitionally) occur in particular in the ventral occipito-temporal (vOT) cortex, a region assumed to be linked by backward connections to regions responsive to phonological and semantic processing. Given the data by Richlan et al. (2011), it is likely that such phonological regions are in posterior superior temporal cortex and posterior inferior frontal cortex; hypotheses about the location of semantically (or lexically) relevant regions can only be based on the broad neuroimaging literature, and will be the focus of the present paper (see below).

Based on their findings about selective impairments in access to phonological or orthographic lexical representations (Bergmann & Wimmer, 2008), Wimmer et al. (2010) systematically investigated the neural pathways supporting access to the visual input lexicon, comparing these between groups of dyslexic and normal readers (for an earlier meta-analysis cf. Jobard, Crivello, & Tzourio-Mazoyer, 2003). All subjects performed a phonological lexical decision task on real words (e.g. TAXI) pseudohomophones (TAKSI), and pronounceable pseudowords (TAZI), deciding whether they sounded like a real word or not. For normal readers, activation increase from words over pseudohomophones to pseudowords was observed, among others, in the left inferior frontal cortex.[1] In contrast, for dyslexics, activation in this region increased from words to pseudohomophones, but not further to pseudowords. This difference was also statistically significant when the contrast pseudowords > pseudohomophones was compared between the two groups, yielding a stronger left inferior frontal effect for normal readers. These findings suggest that normal readers profit from the fact that pseudohomophones sound like lexical entries, whereas dyslexics do not. In other words, one could conclude that lexical access to written stimuli in normal readers is facilitated by the phonological input lexicon in the case of pseudohomophones (i.e. pseudowords that sound like real words), but that lexical access is equally difficult for dyslexics in both the case of pseudohomophones and pseudowords.

Whereas these results by Wimmer et al. (2010) provides substantial insights into the role of phonological lexical information on successful lexical retrieval, the following questions still remain to be answered.

1. Are the neural correlates of lexical access to written stimuli generally altered in dyslexia, i.e. not only in the case of pseudowords (whether or not they sound like a real word) but also in the case of real words to which access is harder because they have lower lexical frequency? Is the observed effect thus a more general effect of lexical access over and above phonological modulation?
2. Given that dyslexics tend to have problems with executive processing and phonological working memory (Beneventi, Tønnessen, & Ersland, 2009; Beneventi, Tønnessen, Ersland, & Hugdahl, 2010a, 2010b), could the left inferior frontal effects in the Wimmer et al. (2010) study be partly due to the metalinguistic lexical phonological decision task? In other words, do differential effects of lexical access to written stimuli in left inferior frontal cortex persist during normal overt reading when no other cognitive demands are posed on the dyslexic readers?
3. Finally, given that adults sometimes overcome their childhood dyslexia, ending up as normal readers (e.g. Chiarello, Lombardino, Kacinik, Otto, & Leonard, 2006; Paulesu et al., 1996; Shaywitz et al., 2003): Would such recovery likewise be reflected in activation differences between pseudo-words, low frequent words, and high frequent words? Would such differences also involve the left inferior frontal cortex?

Consequently, we conducted an fMRI study investigating lexical access in dyslexic adults using three different types of written stimuli: words with low lexical frequency, words with high lexical frequency, and pseudo-words, i.e. words with a lexical frequency of 0 (Binder, Medler, Desai, Conant, & Liebenthal, 2005; Fiebach, Friederici, Müller, & von Cramon, 2002; see also Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). Lexical access is known to rely in particular on Broca's region in the left inferior frontal cortex, involving (at least) areas 44 and 45. Heim et al. (2005), Heim, Eickhoff, and Amunts (2009), Heim, Eickhoff, Ischebeck, et al. (2009) could differentiate the roles of these two areas by means of cytoarchitectonic probability maps (Amunts et al., 1999), showing that area 45 supports lexical selection processes whereas area 44 is more involved in lexical access via the segmental route to reading. Based on this result, a recent neuroimaging study in primary school children (Grande, Meffert, Huber, Amunts, & Heim, 2011) demonstrated that dyslexic readers show stronger activation than normal readers in area 44 during visual lexical access, whereas activation in area 45 was comparable. Consequently, the question is whether these prevail in adulthood. We hypothesise that dyslexic and normal readers differ with respect to brain activation related to lexical access in written stimuli. Given the data by Grande et al. (2011) as well as earlier data on normal readers (Fiebach et al., 2002), we expected effects in particular within Broca's region in the left inferior frontal gyrus.

Finally, in the light of studies revealing differences between compensated and non-compensated adult dyslexic readers (e.g. Chiarello et al., 2006; Paulesu et al., 1996; Shaywitz et al., 2003), it would be interesting to see whether activation differences for lexical access can still be seen in this group of dyslexics. Since four of the 15 dyslexic readers in the present study were compensated, we provide preliminary data on this latter question in the Supplement.

There is an ongoing debate about the optimal fMRI paradigm for investigating lexical access (e.g. Carreiras, Mechelli, Estévez, & Price, 2007; Schurz et al., 2010). Whereas Carreiras et al. (2007) found evidence for an overall comparability of lexical decisions and reading (aloud), the review of the literature by Schurz et al. (2010) is somewhat more differentiating, showing that Lexicality effects (e.g. of pseudowords vs. words) may be comparable in some but not all brain regions, in particular the visual word form area and occipito-temporal cortex. In order to tap reading in a setting as naturalistic as possible, we employed an overt reading task in the scanner, building on previous experience from language production studies e.g. by De Zubicaray, Wilson, McMahon, and Muthiah (2001), Heim, Opitz, and Friederici (2002), or Grande et al. (2011). In this paradigm, lexical access was operationalised in two contrasts, pseudowords > words, and low-frequent words > high-frequent words.[2] Using such naturalistic task, we circumvented potential shortcomings of the use of metalinguistic tasks such as lexical decisions.

[1] The focus of the Wimmer et al. (2010) study was on the left OT region and its function during reading. In contrast, the present paper focuses on lexical access, rather than reporting yet another study on brain activation differences between dyslexics and controls during reading. Therefore, other than in the Wimmer study, the left inferior frontal cortex is of particular importance in the scope of the present paper, because it has been implicated in a series of previous studies on dyslexia that used cytoarchitectonic maps of area 44 and 45.

[2] There is a debate how differences between words and pseudowords, or low vs. high frequent words, are best used to tap lexical processing. It should be noted that the optimal solution depends on the intention of the researchers. As outlined in Heim et al. (2005), if lexical access, i.e. the process of retrieving a lexical entry, is in the scope of the study, the more easily accessible stimulus should be subtracted from the more difficult one, i.e. pseudowords minus words, or low-frequent minus high-frequent words. In contrast, if not the process of lexical access, but rather the analysis of the semantic content is in focus, the reverse contrast, i.e. words minus pseudowords, should be computed. Note that the task (explicit decision vs. e.g. priming) should be chosen respectively.