Neurophysiological studies of reading fluency

Qin, Rui

Chapter 5

General Discussion

Chapter 5 General Discussion

Reading is one of the most important vehicles for human communication and culture propagation. Despite its fundamental role in literate societies, reading is not an innate ability and has to be explicitly taught and learnt. Though most children master the basic principles of reading within the first few years of schooling, about 3 – 10% of children are affected by developmental dyslexia and hence experience tremendous difficulties with learning to read (Lyon et al., 2003; Peterson & Pennington, 2012). To minimize the detrimental effects of dyslexia, it is of vital importance to detect the disorder at an early age so that optimal intervention can be provided in time. The studies reported in this dissertation are intended to reveal early neurophysiological indicators of developmental dyslexia in novice readers of Dutch.

One of the most influential theoretical accounts of reading, the dual route cascaded (DRC) model (Coltheart et al., 2001), proposes that skilled reading proceeds in two pathways, i.e., a lexical/orthographic route supporting whole word recognition and a sublexical/phonological route converting letter strings into phonological representations. While the former requires fast, automatic recognition of visual word-forms, the latter necessitates mastery of grapheme-to-phoneme conversion rules, for which intact auditory discrimination is a pre-requisite (impaired auditory discrimination leads to underspecified phonological representations); therefore, in this dissertation, we investigated early indicators of dyslexia in two domains, i.e. visual word recognition and auditory discrimination, both of which are key components underlying skilled reading.

To fulfil these objectives, we recorded children's event-related potentials (ERPs), i.e., electrical brain activities, while they were performing an implicit reading task with words, pseudowords and symbol strings (for the experiment on visual word recognition, presented in Chapter 2), or were exposed to auditory stimuli under a non-attentive oddball paradigm (for the experiment on auditory discrimination, presented in Chapter 3). In offline analyses of the ERP data, we characterized specific patterns of brain activities in relation to the children's reading abilities, thus revealing neurophysiological markers that help distinguish poor from normal readers.

A major methodological contribution of this thesis is that we used generalized additive modelling (GAM; Wood, 2006) to analyse the ERP data, a novel statistical tool assessing the complete, nonlinear shape of the ERP signal over time. In conventional analyses of ERP data, it has become standard practice to average across multiple trials to obtain an average waveform for each subject, from which peak or mean amplitude is obtained within a pre-defined time window. This practice tends to cause a loss of power in general; moreover, it poses a particular difficulty for studies with children, as ERPs in children typically exhibit larger variability in timing than ERPs in adults. With GAM, we managed to model the nonlinear dynamics of the ERP signal over time, thus avoiding the need for a pre-defined time window of analysis. Another advantage associated with GAM is that, by accommodating nonlinear interactions, GAM allows us to use raw reading scores to index reading ability instead of the categorical factor "poor-reader vs. control". In this way, we were able to characterize the relation between reading ability and the ERP patterns of interest on a continuous, fine-grained scale.

Below we summarize major findings of the ERP experiments presented in this dissertation as obtained from GAM analyses and discuss their relevance to theories of skilled reading and reading difficulty. The chapter concludes with recommendations for further research.

5.1. Visual word recognition in dyslexia: N170 print tuning effect

5.1.1. N170 print-tuning effect: a robust neurophysiological marker of emerging dyslexia

There is substantial evidence that identification of printed words implicates the left ventral occipito-temporal cortex, a region widely known as the visual word form system (VWFS; Cohen et al., 2000). By virtue of experience-dependent cortical plasticity, exposure to print starts shaping the functional properties of the VWFS at the beginning of reading acquisition, and gradually leads to the specialization of this region for written language. At the neurophysiological level, fast, reading-related visual specialization is indexed by enhanced, left-lateralized N170 responses for print (e.g., words, pseudowords, consonant strings, etc.) relative to visual baseline (e.g., symbols, icons or word-scrambles). Such a tuning effect for print has been shown to develop rapidly within the first two years of schooling in typically developing children (Maurer et al., 2006). The finding of attenuated/absent tuning effects in dyslexic children, on the other hand, has generated expectations in the research community that the print N170 may represent a neurophysiological indicator of emerging dyslexia (Araújo et al., 2012; Eberhard-Moscicka et al., 2015; Maurer et al., 2007, 2011).

In Chapter 2, we used GAM to investigate the relation between reading fluency and the size, as well as the lateralization of the N170 print-tuning effect. Our major finding is a positive, almost linear relation between reading score and the size of the tuning effect. This converges with, and furthers, previous findings that the presence/size of the tuning effect discriminates between poor and normal readers. In this regard, our finding lends further support to the validity of the print N170 as a neurophysiological indicator of developmental dyslexia. The second major finding is that a robust N170 print-tuning effect is present only in the left hemisphere, so is the positive relation between reading score and the size of the tuning effect. This adds to existing evidence that the left-hemispheric modulation is a distinguishing characteristic of the print N170 (Brandeis et al., 1995; Brem et al., 2005; Maurer & McCandliss, 2007; Rossion et al., 2003), one that sets it apart from other categorises of visual expertise, e.g., the face N170 and the object N170, which typically exhibit a bilateral or right-lateralized pattern (Latinus & Taylor, 2006; Tanaka & Curran, 2001).

Besides the primary (rather pragmatic) objective of testing the validity of the print-tuning deficit as a diagnostic indicator of dyslexia, it is also of interest to examine the underlying mechanism of the print-tuning effect itself. Although a broad consensus has been reached that print tuning reflects extensive expertise with a particular script, it remains challenging to identify the specific level from which the tuning effect stems. In this regard, two theoretical accounts have been proposed. On the one hand, the phonological mapping theory links reduced N170 tuning for print to the phonological-core deficit of dyslexia (Maurer & McCandliss, 2007; McCandliss & Noble, 2003). Specifically, this theory contends that the gradual specialization of the VWFS, reflected electrophysiologically as an enhanced, left-lateralized N170 response for print, is developed under profound influence of the grapheme-to-phoneme conversion processes that underlie reading in alphabetic scripts. In support of the phonological mapping theory, a positive correlation between phonological decoding ability and the degree of VWFS specialization has been found in typical and

impaired readers (Shaywitz et al., 2002). Moreover, there is evidence that specific reading training focusing on letter-sound correspondences leads to an emerging N170 tuning effect in preliterate kindergarteners (Brem et al., 2010), and in adults learning an artificial language (Yoncheva, Blau, Maurer, & McCandliss, 2010).

On the other hand, the visual familiarity account postulates a perceptual origin of the print N170. In a study by Valdois and colleagues (Valdois et al., 2012), a global report task was administered to dyslexic children and their age-matched controls, in which participants had to report verbally as many elements as possible within letter-, digit-, or colour-strings that were presented for a brief period of time (about 200 ms). Since letter-, digit-, and colour-names are equally familiar, orally reporting elements from each category should engage similar visual-to-phonology mapping processes. Therefore, if dyslexics' poor performance on letter-report tasks were primarily driven by difficulties with phonological processing, the dyslexic group would be equally impaired across all conditions. The results, however, demonstrated impaired letter/digit-string processing but intact colour-string processing in dyslexics. This dissociation was interpreted as providing evidence for the visual familiarity account, as colour strings are visually less familiar than letter- and digit-strings (it is also quite usual to process letters and digits in strings, but not colour patches). Furthermore, in a separate experiment, the dyslexic group was shown to be similarly impaired (compared with the control group) in letter-string report whether a high-taxing phonological task was simultaneously performed or not. Such a pattern of results is only expected if oral report of letter-strings depends primarily on visual processing rather than phonological processing. Taken together, these findings point to a visual familiarity account of deficient letter-string processing in dyslexia.

As discussed above, the phonological mapping account and the visual familiarity account each provides a possible explanation of the underlying mechanism of the print-tuning effect. In the context of alphabetic languages, however, it is challenging to assess these two accounts against each other. This is because orthography and phonology are closely intertwined in sound-based scripts, thus making it difficult to disentangle 'pure' visual aspects of print processing from evoked phonological processes. In this light, non-alphabetic languages, in which the mapping between sound and word form is relatively arbitrary, provide a unique opportunity to unravel the nature of the print-tuning effect. Moreover, an implication for the phonological mapping theory is that the left-lateralization of the print N170 would be robust and pronounced in alphabetic, but not in non-alphabetic languages, because grapheme-to-phoneme conversion hardly exists in the latter scripts (Maurer & McCandliss, 2007). Motivated by such a scenario, in Chapter 4 we investigated whether the enhanced, left-lateralized N170 print-tuning effect extends to Chinese, the most widely used logographic writing system in the world. Interestingly, in addition to the logographic script, a phonetic *pinyin* system is used as an auxiliary means to code Chinese speech in written form. The outcome of this research was expected to provide useful insights in to the underlying mechanism of N170 tuning for print.

5.1.2. Underlying mechanism of the N170 print tuning effect

A common difficulty confronting print-tuning studies is to match control stimuli (e.g., symbols) with print for low-level visual features. This poses particular difficulties to studies with Chinese, because logographic characters, with their uniquely square, compact structure, differ from control stimuli in many aspects other than wordness (the status of being a word); these include visual complexity, string

length, spatial structure, etc. It is not yet clear what features are most critical to control for, and tests of visual similarity are rarely reported in existing studies (Maurer et al., 2008). It is possible that the N170 tuning effects, if observed at all, are (partially) caused by differences in low-level visual features between control and print stimuli and thus do not necessarily reflect reading expertise with the script per se. To avoid such confounds, we adopted a cross-linguistic design including native Chinese readers and native Dutch readers (who could not read Chinese) as controls. Since the two groups of participants viewed the same set of stimuli, any difference in their patterns of tuning, as indexed by the contrast between print (i.e., logographic characters or pinyin strings) and control stimuli (i.e., symbol strings), must be attributed to their differential experience with the Chinese script rather than to low-level stimulus features.

The results revealed that both Chinese and Dutch readers responded more strongly to logographic characters than to symbol strings, but the character – symbol difference was significantly left lateralized in the Chinese group only; the Dutch group demonstrated a bilateral topography instead. With respect to pinyin, both Chinese and Dutch participants showed larger N170 responses to pinyin than to symbol strings; the left-hemispheric modulation, however, was absent in both groups, presumably because it is uncommon to process pinyin in long strings. Taken together, our findings suggest that logographic characters evoke enhanced, left-lateralized N170 responses as do alphabetic words, and that such tuning effect is clearly driven by script familiarity, rather than by differences in visual features between print and control stimuli.

As proposed by Paulesu and colleagues (Paulesu et al., 2001), despite variations among orthographies in the visual form of graphic components and mapping strategies, some principles underpinning reading are shared universally. Crucially, all reading begins with visual analysis, and is dependent on connections to spoken languages. At the neurobiological level, this is reflected by universal activations in the left occipitotemporal cortex (i.e., the neural substrate of the print N170) for the task of reading (Perfetti et al., 2013), a region that presumably supports visual word recognition and links it to language areas. By showing that the left-lateralized print N170 extends to Chinese characters, this thesis provides neurophysiological evidence that alphabetic and logographic reading summon similar visual-orthographic processes.

Since we found a robust N170 print-tuning effect for logographic Chinese script, in which grapheme-to-phoneme conversion hardly exists, our results seem to support the visual familiarity account of the N170 print-tuning effect. The current set of findings, however, does not necessarily weaken the role of phonology in the *development* of visual specialization for print. As Lin and colleagues (Lin et al., 2011) put forward, phonology may play a crucial role in shaping the print N170 during the *initial* stage of reading acquisition. Specifically, when novice readers encounter written words, the left-lateralized phonological system is frequently co-activated with the visual system, leading to the left-lateralization of the print N170. Fluent adult readers, on the other hand, do not necessarily resort to the speech network while viewing visually presented words, especially in implicit reading tasks, thus reducing the contribution of phonology to the left-lateralized N170 in such contexts. In short, influence from phonology and visual familiarity with a particular script each constitutes a possible source for the left-lateralized print N170; whereas the former may play a particular important role at the early stage of reading acquisition (when reading proceeds mainly via the sublexical/phonological route), the latter is likely to gain in importance as

reading becomes increasingly automatic (when a sizable orthographic input lexicon is obtained and the lexical/orthographic route of reading is established).

Given that grapheme-to-phoneme conversion hardly exists in Chinese, one might speculate that the dual-source scenario outlined above would not apply to Chinese, and that the left-lateralized print N170 for logographic characters would be exclusively driven by visual familiarity. Indeed, it is possible that visual word recognition in Chinese is (partially) modulated by phonology in a broader sense, if not by grapheme-to-phoneme conversion in particular. According to the universal phonological principle theory (Perfetti & Harris, 2013; Perfetti et al., 1992), all reading engages phonology at the earliest moment and the smallest unit allowed by the writing system. A similar account was proposed by the grain size theory (Ziegler & Goswami, 2005), i.e., reading procedures assemble phonology according to the grain size of orthography. Specifically, the small grain size of alphabets allows a phoneme-level assembly of phonology, whereas the large grain size of Chinese logographs supports syllable-level assembly. Under these universal hypotheses, reading in both alphabetic and logographic scripts engages phonology; what differs between them is the way phonology is implemented into the writing system (Perfetti et al., 2013). Supporting this view, there is good evidence that phonology is activated when Chinese characters are read for meaning (See Perfetti et al., 2005 for a review). Following this line of reasoning, phonology may very well influence visual word recognition in Chinese, thus playing a role in shaping the left-lateralized print N170 for logographic characters.

5.2. Auditory discrimination in dyslexia: the mismatch negativity

A prevailing view regarding the aetiology of developmental dyslexia is that it originates from a cognitive deficit in representing and manipulating speech sounds. This phonological deficit itself, on the other hand, has been hypothesized to result from a more basic deficit in auditory processing. Motivated by such a scenario, a large body of research has been conducted to evaluate whether performance on tasks assessing auditory discriminability can help distinguish between poor and normal readers (for reviews see, e.g., Hämäläinen, Salminen, & Leppänen, 2013; Näätänen, et al., 2012; Schulte-Körne & Bruder, 2010). The majority of these studies have used the mismatch negativity (MMN), an ERP component traditionally regarded as an objective measure of the accuracy of auditory discrimination (Näätänen et al., 2004; Näätänen & Winkler, 1999). Since the MMN can be readily elicited using a passive, non-attentive paradigm, it provides a useful adjunct to behavioural assessments of auditory discriminability in young children and clinical populations who have difficulty with psychoacoustic tasks.

In Chapter 3, we thus used an oddball paradigm to investigate the relation between reading fluency and the presence/size of the mismatch response. Both speech (syllable) and nonspeech (tone) stimuli were included, with the size of the deviant stimuli manipulated (small vs. large). Our results show that, overall, the size of the mismatch response was not systematically related to reading score in either condition. For the tones, exploratory analyses revealed a positive, albeit moderate, correlation between reading score and the size of the MMN to *small* deviants in the left hemisphere. For the syllables, mismatch responses were found, also for *small* deviants, at midline electrodes in time windows corresponding to the classic MMN and a late discriminative negativity (LDN); the size of these mismatches, however, was not reliably related to reading performance.

So far, the literature on MMN and dyslexia has been highly inconsistent, with some studies reporting attenuated MMN in dyslexics and others failing to reveal significant group differences between dyslexic and normal readers (for a review see Bishop, 2007; Schulte-Körne & Bruder, 2010). Using GAM to accommodate the numeric (and potentially nonlinear) predictor Reading score, we characterized the relation between reading ability and the presence/size of the mismatch response on a continuous, fine-grained scale. Yet, we did not find any indication for a robust correlation over the entire timespan wherein the mismatch response might emerge. A more fundamental issue that casts doubt on the validity of the MMN as the electrophysiological correlate of auditory discrimination is that the presence/size of the MMN often fails to converge with behavioral discrimination measures. There is even evidence that the MMN is absent in a large percentage of healthy adults, especially for easily discriminable standard-deviant parings (e.g., Pettigrew et al., 2004; the large deviants in the tone/syllable condition in our study).

A lot of methodological factors might account for the mixed results regarding the reliability of attenuated MMN as a diagnostic index for reading disability. As has been shown in the current study and in many earlier studies, deviance size seems to play a role, so that small deviants are more likely to distinguish dyslexic from normal readers (frequency change in percentage < 10%; Bishop, 2007). This might be taken as evidence that the auditory discrimination deficit in dyslexics surfaces only when the difference between the standard and the deviant is subtle. On the other hand, the mismatch response to speech stimuli is also highly variable depending on stimulus features. For example, the contrast between /ba/ and /ga/ (e.g. Sharma et al., 2006; Uwer et al., 2002) has a better chance of eliciting significant group differences than that between /ba/ and /da/ (e.g. Sebastian & Yasin, 2008; our study). Such a pattern of results, though not fully understood yet, suggests that specific spectral features of speech sounds may pose particular difficulties for dyslexic readers. Another factor that has a notable impact on the mismatch response is presentation rate: significant differences between dyslexic and control groups are more often seen with rapid (stimulus onset asynchrony < 500 ms) than slow presentation rates (Bishop, 2007).

Besides the methodological factors listed above, another potential explanation for the lack of correlation between reading ability and the presence/size of the MMN is that the putative auditory deficit of dyslexia is not directly related to reading difficulty, and therefore does not become manifest unless specific mediating factors are present. Specifically, poor performance on oral language tasks in children with reduced MMN suggests that deficient auditory discrimination may be associated with impaired oral language skills, rather than classic dyslexia (Bishop, 2007). In a prospective longitudinal study, Boets and colleagues (Boets, Wouters, van Wieringen, De Smedt, & Ghesquière, 2008) provided a succinct account of how a low-level auditory processing deficit leads to impaired speech perception, disrupted phonological development, and ultimately to literacy problems. Using causal path analysis, the researchers found that preschool measures of auditory processing were related, both directly and indirectly (mediated via speech perception), to those of phonological awareness, which in turn predicted literacy achievement at the end of first grade. Auditory processing itself, however, was not directly related to literacy measures. Considering the role of phonological awareness as a mediating factor linking auditory processing to reading fluency, in future research it would be useful to subdivide dyslexic readers into those with and without phonological deficits, and test whether the two groups would be differentially impaired in auditory processing.

5.3. Concluding remarks

In this thesis, we chose to investigate neurophysiological markers of emerging dyslexia in two domains, i.e., visual word recognition and auditory discrimination. Along both lines of research, we assessed very basic aspects of perceptual processing that constitute critical first steps in deciphering visual/oral language codes. There are two reasons for this selection. First, given our dedication to *early* diagnosis of developmental dyslexia, it is important to focus on aspects of perceptual/language processing that can be easily tested in young children, preferably under non-attentive paradigms. Secondly, several widely implemented remediation programs, at least in Europe, are based on the assumption of basic visual or auditory perception deficits in dyslexia (Schulte-Körne & Bruder, 2010). To ensure efficient execution of the intervention plans, it is crucial to examine their empirical basis. Overall, our findings suggest that the N170 coarse tuning effect (i.e., enhanced, left-lateralized N170 response for print) is a valid neurophysiological indicator of dyslexia, one that can be readily elicited by implicit reading tasks and robustly detected at the individual level. On the other hand, the relation between reading ability and the mismatch negativity is less systematic, and is highly dependent on a series of methodological factors.

5.4. Directions for future research

1. Study population: Since neither the auditory discrimination nor the visual word recognition deficit seems adequate to account for the full spectrum of impaired reading patterns, it would be useful to relate these two deficits to subtypes of developmental dyslexia. This is in line with the claims of the hybrid model (Pennington, 2006; Pennington, et al., 2012), i.e., there is no single etiological or cognitive factor that is sufficient to cause dyslexia; rather, dyslexic symptoms observed at the behavioural level can be traced back to various combinations of underlying cognitive deficits. In future research, it would be advisable to subdivide the dyslexic group on the basis of their cognitive-linguistic profiles, and investigate whether different subgroups exhibit different patterns regarding visual word recognition and auditory discrimination.

2. Statistics: A limitation of the GAM approach implemented in this thesis concerns the subjectivity involved in the selection of the channels for analyses. Indeed, GAM can be used to model the topography of the ERP signals over the entire scalp, e.g., by creating a tensor product combining time and electrode position (coded with x and y coordinates). However, such an approach is currently too computationally intensive. In future research, advances in the software would likely allow such complex modelling to take into account individual electrodes, thus offering a more complete representation of the data.

3. A possibility of linking N170 to MMN: As hypothesized by the phonological mapping theory, the print-tuning deficit can be traced back to difficulties with phonological processing. Since the MMN presumably indexes the accuracy of auditory perception, which itself is closely related to phonological processing, it would be impactful to investigate the relation between the print N170 and the MMN (probably in combination with measures of phonological processing as mediating factors).