Speaking of reading: The role of basic auditory and speech processing in the manifestation of dyslexia in children at familial risk
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Chapter 6

General Discussion

Whether or not dyslexia manifests itself depends on a great variety of factors. For a child, the risk of developing dyslexia greatly increases when one, or both parents are dyslexic (Carrion-Castillo et al., 2013). However, in children with a genetic risk, it is not clear which factors contribute to them eventually becoming dyslexic, or not. This thesis aimed to further our knowledge of factors that contribute to the manifestation of dyslexia, by examining familial risk (FR) children who did and did not become dyslexic. Auditory- and speech processing factors were the specific focus. The following paragraphs discuss the results of the neurophysiological studies on basic auditory processing and speech processing (Chapters 2 and 3). Following, results regarding lateralization of speech processing are examined (Chapters 3 and 4). Lastly, results regarding a possible cascading relation between speech processing, phonology, and reading are discussed (Chapter 5).

Neurophysiological indices of basic auditory and speech processing

In the study described in Chapter 2, basic auditory processing, specifically amplitude rise time (ART), was assessed in FR children with and without dyslexia. ART, frequency, and intensity (INT) processing were measured using event-related potentials (ERPs). ERP components of interest were the mismatch negativity (MMN) and the late discriminative negativity (LDN), both reflective of change detection (Cheour et al., 2001; Näätänen, 1995). LDN results indicated that all groups of children were sensitive to differences in ART. To frequency deviants, FR children showed an attenuated MMN compared to control children, but a normal LDN. Changes in INT were not detected by the auditory system of FR
children as indicated by an absence of MMN and LDN response. Control children, on the other hand, did have a significantly larger LDN to intensity than FR children.

Our results regarding basic auditory processing diverge from previous studies. Remarkably, we did not observe any group differences on ART processing, while other ERP studies investigating ART processing found smaller LDN amplitudes at age 9 (Hämäläinen et al., 2008) and smaller N1s (reflective of sensory processing; Hämäläinen et al., 2007) in poor readers. Behavioral findings point toward differences in ART processing between dyslexic and typical readers (e.g. Richardson et al, 2004; Goswami et al., 2002; Muneaux et al., 2004). In these studies, adaptive paradigms are frequently used that require a high cognitive load. It is thus likely that the task demands of these behavioral studies may have influenced the outcomes, especially given the comorbidity of attention problems in dyslexia (e.g. Moll et al., 2014). Since our study has measured basic auditory processing pre-attentively we do not have such a confound. Possibly, the different findings regarding ART processing are caused by the fact that other studies did not control for family risk for dyslexia. If ART processing deficits, or any type of deficit, is visible to an equal extent in FR children with and without dyslexia, then this deficit is not specific to the manifestation of reading problems. It is thus possible that not including FR children without dyslexia could have let to too strong conclusions regarding the relationship between ART processing deficits and reading problems. Regardless, our results suggest that there is no deficit at all in ART processing at age 11, irrespective of familial risk or reading status, and that a deficit in INT processing is related to familial risk status, not to reading fluency. When connecting these results to the main question of this thesis it appears that basic auditory processing problems are not crucial to the manifestation of reading problems.

In the study described in Chapter 3, auditory speech processing was investigated in order to examine the influence of speech processing on the manifestation of reading problems. Children were presented with a natural speech vowel contrast (/a:/ vs. /o:/), and with words, specifically the verb zie ("see") vs. its inflected form ziet ("sees"). These types of stimulus contrasts were used to assess the role of lexicality. Additionally, it enabled us to address lateralization of speech processing in dyslexia – as processing of inflected verbs is thought to lateralize more strongly than processing of vowels (Shtyrov et al., 2010; lateralization is further discussed in the next section). There was no difference between the LDN amplitude of vowels and words, indicating no effects of lexicality. However, overall smaller LDN amplitudes were observed for the FRD group compared to controls and
FRND children. Dyslexia status was predictive of a lower LDN amplitude when processing speech. Contrary to findings in the realm of basic auditory processing, results from this study tentatively suggest that attenuated speech processing is related to reading problems, not to familial risk.

The findings of these two neurophysiological studies imply that processing ART does not relate to reading or FR, whereas processing of linguistic information like speech is deficient in FRD children only, irrespective of the lexicality of the stimulus. In light of previous DDP studies, these findings are of particular interest. Plakas et al. (2013) found ART processing to be impeded in 41-month-old children at FR for dyslexia. FRND as well as FRD children showed an attenuated sensitivity to changes in ART. From our results, it seems that FR children overcome this deficit as they grow older, since all groups of children were able to discern subtle differences in ART at age 11. The results of these two studies combined suggest different developmental trajectories for basic auditory processing in FR children compared to controls, resulting in a longer time needed to attain similar levels of processing. This would have to be confirmed by a longitudinal analysis. Note that ART processing, however, does at neither age relate to reading problems that dyslexic children have, since all children at familial risk display this pattern for ART processing.

Regarding speech processing, our study corroborates previous DDP findings by Van Zuijen et al. (2013), who found electrophysiological evidence of speech processing to be impeded in 2-month old FR infants who would later become dyslexic. Although we were not able to address auditory- and speech processing longitudinally in the same group of children, the findings of Van Zuijen et al. (2013) and Chapter 3 combined suggest that infant speech processing deficits are a precursor of reading problems, and that speech processing deficits are also present at the end of primary school in children who have dyslexia. Evidence from other studies shows that these neural deficits in speech perception in dyslexia even persist into adulthood (e.g. Schulte-Körne et al., 1998), although in the latter study differences between FRND and FRD groups were not assessed.

**Speech processing and hemispheric lateralization**

The studies in Chapters 3 and 4 investigated lateralization of speech processing, to examine whether atypical lateralization contributes to the manifestation of dyslexia. To shed more light on the contribution of lateralization of speech processing to reading problems,
lateralization of speech processing was investigated using ERPs and dichotic listening (DL). In our ERP study, we included an inflected verb in our stimuli, next to a simple vowel contrast, to be able to address the influence of lexicality on lateralization, since previous findings indicate inflected verbs to lateralize most strongly (Shtyrov & Pulvermüller, 2002). Chapter 4 addressed lateralization of speech processing behaviorally, using the DL method with speech stimuli in Grades 3 (digits) and 5/6 (CV syllables). The two time points allowed us to address lateralization of speech processing over time.

Results from the ERP study in Chapter 3 suggest processing of speech to predominantly take place in the left hemisphere for FRD, FRND, and control children, as all groups have a dominant left hemisphere LDN. Contrary to previous findings (e.g. Shtyrov & Pulvermüller, 2002), a simple vowel contrast yielded similar results as a grammatically inflected word pair. Left lateralization was thus independent of stimulus lexicality. The ERP outcomes from Chapter 3 converge with the results in Chapter 4, that show no differential lateralization of speech processing in a DL paradigm. All groups of children show a right ear advantage, both in 3rd and 5th/6th Grade, implicating a dominant role for the LH in speech processing for all groups. Overall, our results show that more symmetrical lateralization of speech processing is not a factor that distinguishes poorly reading children from fluently reading children, and that it is not a characteristic of FR children, either. Reading problems cannot be ascribed to more symmetrical processing of speech.

Interestingly, our DL results showed a reduced number of reports from the left ear in the FRD group, in line with findings by Moncrieff and Black (2008) and Morton and Siegel (1991). FRND and control children were significantly better at correctly reporting items from this ear. Therefore, a reduced left ear report is associated with reading skill. This possibly indicates an enlarged left laterality, which may stem from reduced right hemisphere activity. Results from the directed attention (DA) paradigm in Chapter 4 show that, despite an increase in the amount of left ear reports as a function of a left ear probe, FRD children always report less from their left ear compared to FRND and control children. In other words, when asked to focus on the left ear, the FRD group does not attain a similar amount of left ear reports compared to controls and FRND children either. These results tentatively suggest that the lower amount of left ear reports might stem from impediments in right hemisphere higher-level processes such as attention (Kershner & Morton, 1990). Previous work in fMRI in healthy adults has demonstrated the involvement of frontal right hemisphere networks in a DA-left condition, versus areas associated with
phonology in the LH in a DA-right condition (Jäncke & Shah, 2002). This suggests that different processing activity underlies the two different conditions. Whether the reduced left ear reports in poor readers indeed stem from lower activation of right hemisphere networks associated with attention, will have to be further explored by a DL study that incorporates neural and behavioral measures of DL as well as attention measures in a familial risk population. Nevertheless, our finding that overall, right ear reports are being made most often, shows that attentional control is not the only variable controlling right- or left ear responses. This is likely due to the LH dominance for processing speech, that results from a ‘hard wired’ connection between the right auditory cortex and left hemispheric areas responsible for linguistic processing (Scott & Wise, 2004; Hugdahl et al., 1998).

Although in line with the idea that in most individuals, speech processing is lateralized to the LH (Dehaene et al., 1997), generally, our results regarding lateralization do not converge with other ERP studies that found different patterns of activation in dyslexia (e.g., Lovio et al., 2010; Lyytinen et al., 2005) or with other neuroimaging results that have shown lesser activity in specific LH areas such as the visual word form area (e.g., McCandliss & Noble, 2003; Shaywitz et al., 1998) or more activity in RH areas in dyslexia (e.g., Sandak et al., 2004). Neuroimaging methods, however, allow for a more exact localization of activity, which facilitates better identification of lateralization differences. Neither scalp ERP measures nor dichotic listening are able to pinpoint the exact locus of activity, and are therefore less sensitive. In the current studies, possible differences in lateralization might have been overlooked. Though our findings clearly suggest differences in lateralization to be absent, neuroimaging studies using fMRI or DTI in conjunction with behavioral DL measures could shed further light on the role both hemispheres assume in speech processing in dyslexia.

**Speech perception and its relation to phonological processing and reading**

To deepen our understanding of the relations between speech processing, phonological processing, and reading, categorical perception (CP) of speech and its relation to phonological skills and reading were assessed in Chapter 5. The contribution of a deficit in CP to the manifestation of dyslexia was assessed, as well as the existence of a possible cascading relation from deficits in speech perception to phonology to reading.
We investigated CP in 3rd graders. Our results show that FRD children are better at perceiving within-category phonemes compared to good readers. This is indicative of poorer categorical perception, since differences between within-category tokens are not phonemic in nature and therefore, being able to perceive these differences is superfluous. These results suggest impaired CP to contribute to the manifestation of dyslexia. The results converged with, and extended findings of other studies that have observed CP impairments in young FR children at a pre-reading age (Boets et al., 2011; Gerrits & De Bree, 2009), showing that deficits in CP persist in FRD children after reading onset. Placing these results in the context of similar findings in adults with dyslexia (e.g. Messaoud-Galusi et al., 2011), this could mean that CP deficits exist throughout the lifespan.

Chapter 5 also assessed the cascading relation between speech, phonology, and reading. In case problems in speech perception are at the root of phonological problems and reading, we expected deficits in CP as well as deficits in phonology to surface in the FRD group. We indeed observed such a pattern. In line with previous studies, problems in phonological processing skills such as phonological awareness (PA), rapid naming (RAN), and nonword repetition (NWR) proved to be specific to poor readers, underlining the importance of apt phonological skills in acquiring reading ability (e.g. Vellutino et al., 2004; Moll et al., 2013). Another prerequisite for a cascade to be present, was an observed relation between measures of CP and phonological processing and reading. Yet, CP did not predict NWR or PA, which was remarkable since we had expected to find relations between these variables. However, CP did significantly predict RAN and reading. Results of a mediation analysis indicated that the relation between CP and reading was fully mediated by RAN. CP thus ceases to predict reading skill when RAN is taken into account. Possibly, this is due to the fact that RAN builds on the same basic processes like reading, such as automaticity, and is therefore highly similar to reading in itself (Norton & Wolf, 2012). Another interpretation is that performance on RAN and CP is determined by similar underlying processes, such as processing speed, which has previously been related to reading skill (McGrath et al., 2011). Overall, due to the absence of relations between CP and two out of three measures of phonological processing, PA and NWR, the results of our CP study do not convincingly support the cascading theory.

The other studies presented in this thesis do not provide clear evidence that a cascading relation between basic auditory or speech processing, phonology and reading is present either. In Chapter 2, firstly, the measure on which we thought to find differences between
good and poor readers, ART, did not yield any group differences. Secondly, ART MMN and LDN amplitudes did not correlate with behavioral measures of phonological processing or reading ability. Despite speech evoked LDN amplitude differences reported in Chapter 3 between FRD children and good readers, an explorative analysis of correlations between speech processing LDN amplitudes, phonological skills and reading, showed no relation either (see Appendix). Chapter 4 results show that, despite differences between good and poor readers, correlations between the lateralization index of speech processing, phonological skills and reading in Chapter 4 are absent in Grade 5/6. In Grade 3, the lateralization index correlated with reading measures, but not with phonology. A study by Ramus and colleagues (2003), investigating the relation between auditory processing and phonology in dyslexic readers, demonstrated that relations between a general compound measure of auditory processing and phonology are present. However, despite the fact that this general measure of auditory processing did contribute to the variance in phonological tasks, no consistent relations were identified between individual auditory processing constructs (such as rapid auditory processing or speech processing) and phonological processing, as measured by RAN, NWR, and spoonerism tasks. The authors therefore concluded that some aspects of auditory processing might affect aspects of phonology more so, than others. Our findings are in support of this view, since they show that generally, the speech processing factors measured in our studies do not seem to act on phonology at all, except CP on RAN.

The results of the studies in this thesis are in agreement regarding the role of phonology in reading. All chapters show phonological skills to be consistently impaired in the FRD group. Moreover, phonological skills correlate with word- and pseudoword reading fluency. These results are in line with the literature on phonology and dyslexia (e.g. Vellutino et al., 2004; Moll et al., 2013), and underline the important link of phonological skills and reading. Overall, the presented studies do not find clear evidence for basic auditory processing and speech processing to be part of a cascade of problems, serving underlying processes that act on phonological processing (e.g. Tallal, 1980). This could mean that the level of phonological processing might thus be the lowest level at which deficits can occur that lead directly to reading problems. Any deficits observed in speech processing are possibly separate problems acting on reading processes. This idea fits nicely with the multiple deficit model for dyslexia, that points toward an interaction of several genetic, neural, cognitive, behavioral and environmental factors that together contribute to a reading problem (Pennington, 2006). In the context of the aim of this thesis, this means that pre-attentive
speech processing, CP, as well as a decreased left ear report in dichotic listening are factors that in their own way contribute to the manifestation of dyslexia, parallel to the ‘usual suspects’ RAN, PA, and NWR, where the relation between CP and reading is mediated by RAN. Deficits in basic auditory processing on the other hand, are characteristic of being at FR for dyslexia and not specifically related to reading fluency. In cases where deficits are present in all FR children, dyslexia might become manifest if these deficits co-occur with other deficits (Pennington, 2006). Alternatively, deficits relating to FR could in the end just be an epiphenomenon of genetic risk and not be related to eventual reading skill. After all, genes associated with reading ability do not exclusively relate to reading ability. More so, they are implicated in complex processes such as neuronal migration, a process not specific to neural networks associated with reading, but which might ultimately affect reading circuitry (Fisher & Francks, 2006).

**Implications and future directions**

The outcomes of the presented studies show that basic auditory processing problems were related to familial risk, not to reading. Importantly, ART processing, our measure of interest, related to neither FR nor reading. This might have important implications for practice, such that auditory processing interventions (e.g. Thomson, Leong, & Goswami, 2013) might not be very beneficial in elevating reading fluency. Regarding speech processing, the presented studies have clearly shown that differences between good and poor readers exist on multiple aspects of speech processing and multiple levels (neural, behavioral) of measurement. This implies that there is a variety of speech processing deficits that may occur in poor readers, that are all aspects that distinguish them from averagely reading children at familial risk. For FRND children, this could mean that unimpaired speech processing might be one of the factors that compensates their genetic liability for reading problems. On other (early) language related measures, such as expressive and receptive vocabulary, FRND children have been shown to outperform FRD children as well (e.g. Torppa et al., 2010). Language development in a more broad sense may thus serve as a protective factor. From our studies, however, it does not become clear whether the identified speech processing deficits are precursors for dyslexia, since the data we report were collected in Grades 3, and 5/6. This means that our results cannot be used for purposes of early identification of reading problems. Additionally, though the facets of speech processing assessed in this thesis separate FRND from FRD children, using them for diagnostic purposes is, given their relative influence on and relation to reading outcome in
comparison to phonology, probably less important compared to the assessment of phonological skills. A deficit in phonology still seems to be the most important denominator in determining reading problems in familial risk children.

The findings of this thesis stress the theoretical importance of continuing the investigation of the relation between speech processing, familial risk and reading ability. ART, the basic auditory processing measure of interest, is according to theory important for detecting rhythm in speech (Goswami et al., 2002). In our study, differences in ART presented through basic tones proved to be discernible, independent of reading level or familial risk status. However, linguistic information like speech (e.g. neural speech processing, categorical speech perception) consistently separated FRD from FRND and control children. Overall, these results show that, within the age-range specified in our studies, suprasegmental features of speech that are presented without any speech context, like rhythm (measured by ART processing), do not contribute to reading skill. In contrast, linguistic information conveyed in a speech context, such as cues on formant transitions, or lexical or phonemic information, does contribute to reading skill. Possibly, this differentiation finds its origin in processing networks. The findings could indicate that suprasegmental features, especially when presented outside of a speech context, are not primarily treated as speech by the brain. Suprasegmental features like pitch and rhythm have previously shown to be predominantly processed in the right hemisphere, whereas linguistic (phonemic) information is predominantly processed in the left hemisphere (e.g. Liem, Hurschler, Jäncke, & Meyer, 2014; Poeppel et al., 2004; Rinne et al., 1999). Given these findings, it is of interest to deepen our understanding of the relation between reading and speech processing in the future, thereby taking the distinction between suprasegmental and phonemic or lexical information in speech and their respective relations to reading skill as a starting point.

How reading and speech processing are connected exactly, still remains unsure. In our studies, clear (cascading) relations between speech processing, phonological skills, and behavioral reading outcomes are absent. Possibly, the connection between speech processing and reading thus mainly exists because of shared cognitive and neural processes (Ziegler et al., 2009). After all, current models of speech perception (Hickok & Poeppel, 2007) and studies investigating reading networks in the brain (e.g. Schlaggar & McCandliss, 2007; Pugh et al., 2008) identify similar brain regions that are involved in both reading as well as speech processing. How this overlap in networks for speech perception
and reading then contributes to reading ability should be addressed in future studies, since, as noted above, proficient speech processing might compensate a child’s genetic liability to develop reading problems. Stages in and aspects of speech perception that might be crucial for reading should be identified using both behavioral and neuroimaging methods. In doing so, it is important to continuously address the relation of speech perception to behavioral reading- and reading related skills, such as phonological processing. By placing this in the context of familial risk, future studies could paint a more complete picture regarding which speech processing factors relate to reading, and in which manner these contribute to the manifestation of dyslexia.