

/Aba/ or /ada/, that is the question

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Summary

The aim of this dissertation was to explore letter-speech sound processing in typically reading children and children with developmental dyslexia using a longitudinal three-year fMRI design. We employed a novel text-based recalibration paradigm where we bias the perception of an ambiguous speech sound in the direction of disambiguating text (text-based recalibration). This allowed us to tap into short-term audio-visual learning mechanisms involving letter-speech sound mapping in children with varying reading proficiency. Our design further allowed tracking the developmental changes in brain activation associated with letter-speech sound processing across the three-year period.

Summary

Reading is a fundamental skill that facilitates employability, cultural, societal and scientific advances as well as communication between people. However, it is a culturally acquired skill that the human brain has learnt to accommodate through functional and structural plasticity mechanisms that link visual and speech processing areas (Rueckl et al., 2015; Van Atteveldt et al., 2004). One of the proposed pillars of successful reading development is the automatization of letter-speech sound mappings. Difficulties in creating such automatic links have been suggested to underlie reading difficulties in readers with dyslexia (Aravena, 2017; Blomert, 2011), particularly in languages with fairly consistent letter-speech sound mapping such as Dutch. In the longitudinal research study reported in this dissertation, our aim was to investigate letter-speech sound mappings employing a text-based recalibration paradigm in 8-11 year old children of varying reading proficiency, including readers with dyslexia and to link our findings to children's reading and phonological skills.

The project started with a behavioural study investigating text-based recalibration effects in 8-year-old children with and without dyslexia, described in chapter 2. We observed significant recalibration effects in children with and without dyslexia, namely the children's perception of an ambiguous /a?ɑ/ sound mid-way between an /aba/ and /ada/ sound was biased by the simultaneous presentation of this sound with clear "aba" or "ada" text stimuli. This resulted in a perceptual shift reflected in a tendency to perceive the ambiguous speech sound in line with the text (i.e. as /aba/ following "aba" text exposure and as /ada/ following "ada" text exposure). Unlike a previous study reporting a lack of text-based recalibration in adult readers with dyslexia (Keetels et al., 2018), our

findings in children did not reveal any group differences in task performance. The effect was however, positively associated with perceptual adaptation in the dyslexic readers. During the adaptation paradigm, the children were exposed to unambiguous matching letter-speech sound pairs. This elicits the opposite perceptual effect compared to recalibration – fewer responses in line with text – i.e. more /ada/ responses following “aba” sound + text exposure and more /aba/ responses following “ada” sound + text exposure. The reason why such a positive association was only observed in children with dyslexia remains to be investigated. The analyses were further extended to a larger sample of only typically reading children and showed that children who had a well-defined /aba/ - /ada/ phoneme boundary showed stronger recalibration effects, indicating that phonological perception affects the magnitude of text-based recalibration. Moreover, a more distinct phoneme boundary was associated with better reading accuracy, pointing to a close association between phonological processing and reading outcome. Overall, the findings of comparable recalibration effects in children but not in adults with and without dyslexia could indicate a developmental trajectory in audio-visual processing of letters and speech sounds. Indeed, the children in both groups were in the early stages of reading development when brain circuits for letter-speech sound processing are still being fine-tuned. Additionally, the dyslexic readers were in the first months of remediation specifically focused on letter-speech sound mappings. Once the children with and without dyslexia start to reach a stable level of reading fluency with continued reading development, they may rely on partly different brain networks/areas for audio-visual integration and reading, possibly leading to the observed behavioural differences in adults.

In chapter 3, we investigated cortical activation in 9-year old children with and without dyslexia while they performed the text-based recalibration task in the MRI scanner during the first longitudinal measurement. Our aim was to explore the neural mechanisms associated with text-based recalibration and to investigate potential group differences in cortical activation despite the comparable behavioural task performance. In line with the behavioural findings reported in chapter 2, we did not observe any differences in recalibration task performance between the groups. The magnitude of the text-based recalibration effect was, however, reduced in the MRI and - at the group level - no longer reached significance. This could be linked to contextual effects of performing the task in the MRI environment, including the background scanner noise and sound quality in the MR-compatible headphones. Moreover, previous research has shown that the

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scanner noise can reduce (visual) attentional focus in the MR environment (Kobald et al., 2016; van Maanen et al., 2016), as 9-year-old children are still developing their attentional skills (e.g. Amso & Scerif, 2015), they may be especially susceptible to such effects. Overall, children in both groups showed comparable cortical activation in brain areas associated with audio-visual integration and reading and typically reported in studies employing congruency manipulation paradigms in children (Blau et al., 2010; Plewko et al., 2018) and recalibration studies in adults (Bonte et al., 2017; Kilian-Hütten et al., 2011). Nevertheless, children with dyslexia did show less activation in a left hemisphere fusiform region compared to typical readers during the simultaneous presentation of text and ambiguous speech. Across participants, cortical activation within this region was positively correlated with reading fluency and phonological skills. These observations corroborate previous research showing a reduced response in the left fusiform in children with dyslexia, as well as an association between fusiform activation and reading proficiency. The correlation with phonological processing likely reflects maturational processes in this area from multimodal (auditory and visual) processing in children within our age range to unimodal (visual only) stimulus processing in experienced readers (Church et al., 2008). We also observed a correlation between activation within bilateral superior temporal gyri and children's letter-speech sound identification fluency in the entire sample. This indicates an increased involvement of auditory cortical regions during audio-visual processing of letters and speech sounds in children with less automatized letter-speech sound associations. Taken together, our findings illustrate the reading-dependent inter-individual variability in cortical responses to audio-visual letter-speech sound stimuli in 9-year old typical and dyslexic readers.

In chapter 4, we explored longitudinal changes in cortical activation in response to the audio-visual ambiguous speech and text stimuli over a three year period consisting of annual MRI measurements in a group of 8-11 year-old typically reading children. Behaviourally, recalibration did not reach statistical significance in any of the three measurement sessions, similarly to the results of chapter 3. However, the overall magnitude of the effect did increase from session 1 to 3 and approached significance by the last measurement, potentially reflecting a developmental trend in the text-based recalibration effect. Cortical activation elicited by the audio-visual speech and text stimuli across sessions largely overlapped with the network seen in chapter 3 and spanned brain areas associated with audio-visual integration and reading. While upon visual inspection, this network appeared to broaden from measurements one to three, comparisons of cortical

activation between sessions only revealed a significant difference in activation between sessions 1 and 2 in a left hemisphere superior temporal gyrus region. The activation within this region was found to follow an inverted-u-response, showing a peak in activation in session 2 that was linked to children's age. Specifically, the peak was observed in children who were on average 9 years old during the second measurement. We did, however, observe inter-individual variability in the functional activation trajectories across the sessions indicating potential differences in the timing of the peak and/or variability in the brain regions involved in letter-speech sound mapping. The inverted-u-trajectory of left superior temporal gyrus activation is in line with previous studies reporting a similar response pattern in higher order visual areas (Gorka Fraga González et al., 2017; Maurer et al., 2006, 2011, 2008; Price & Devlin, 2011) and can be explained in terms of more general skill learning mechanisms in children. It has been proposed that learning a new skill involves active mechanisms e.g. explicit mapping between letters and speech sounds during reading instruction as well as passive, statistical and associative learning that for example facilitates automatic processing of text in fluent readers (Siegler, 2005). Applied to reading development, the inverted-u trajectory likely reflects the switch from explicit/effortful letter-speech sound mapping to automatized, fluent reading. The reported peak in cortical responsiveness to text around age 9 has furthermore been proposed to be associated with predictive coding mechanisms in higher order visual areas, and taken to represent cortical activation due to high prediction errors that later decrease resulting in a downward slope in activation with improved reading fluency (Price & Devlin, 2011). Given the involvement of the auditory and visual cortices in letter-speech sound mapping, their similar developmental trajectories may reflect a more global developmental pattern of the reading network.

The three empirical chapters of this dissertation report findings of a novel text-based recalibration paradigm previously only researched in adult readers and represent the first behavioural and neuroimaging results using this paradigm in children. The combination of ambiguous speech and text allowed us to explore letter-speech sound processing in children with varying reading proficiencies using short-term perceptual learning rather than over-learned matching and non-matching letter-speech sound pairs that may be influenced by processing or task strategies involving implicit/explicit matching of the stimuli, or children's self-beliefs regarding e.g. their reading ability. Our behavioural results showed comparable text-based recalibration effects in all children, indicating that there were no overall differences in task performance between children

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with and without dyslexia. We did however, observe differences in brain activation between the groups, with dyslexic readers showing less activation in a left hemisphere fusiform area compared to typically reading children that furthermore scaled with children's reading and phonological skills. Activation within this brain region has previously been associated with reading proficiency and automatic processing of text in experienced readers (Ben-Shachar et al., 2011; Dehaene-Lambertz et al., 2018; Pugh et al., 2001). The reported difference in activation between children with and without dyslexia could therefore point to differences in the level of automatization of letter-speech sound mappings and the use of alternate brain areas to perform the same task in dyslexic readers. A longitudinal investigation of brain activation during recalibration task performance in typical readers revealed an age-driven increase in left superior temporal gyrus activation around age 9 compared to ages 8, 10 and 11. This finding indicates a heightened cortical response to audio-visual letter-speech sound stimuli around this age. Taken together, our research highlights the dynamic inter-individual variability in cortical activation during audio-visual integration of letters and speech sounds in children aged 8-11 during the first years of reading instruction and its close association to children's reading and phonological skills.