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Visual, Auditory, and Visual–Auditory Speech Processing in School Children with Writing Difficulties

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„Wer das Alphabet erschaffen hat, hat uns den Faden unserer Gedanken und den Schlüssel der Natur in die Hand gegeben.“

-Antoine de Rivarol-

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Content

Zusammenfassung

Erfolgreicher Schriftspracherwerb erfordert auditive Sprachverarbeitung, visuelle Verarbeitung und die Integration visueller und auditiver Informationen. Personen mit beeinträchtigten schriftsprachlichen Fähigkeiten zeigen auditive Sprachverarbeitungsdefizite. Im Gegensatz dazu ist die Rolle der visuellen Sprachverarbeitung in diesem Zusammenhang wenig untersucht. Das hier vorgestellte Forschungsvorhaben wurde konzipiert, um den Zeitpunkt in der Entwicklung zu identifizieren, an dem Fähigkeiten zur auditiven Sprachverarbeitung beginnen, Schriftsprache vorherzusagen. Des Weiteren sollte neben auditiver, auch visuelle und visuell-auditive Sprachverarbeitung bei Schulkindern mit schriftsprachlichen Schwierigkeiten, hier als Schreibprobleme (SP) definiert, untersucht werden. Dazu wurde das ereigniskorrelierte Potential Mismatch Response in Reaktion auf auditiv präsentierte Silben bei Babys und in Reaktion auf auditiv, visuell und visuell-auditiv präsentierte Silben bei Schulkindern analysiert. Im Alter von 5 Monaten zeigten sich bereits auditive Sprachverarbeitungsunterschiede zwischen Babys mit und ohne spätere SP—ein Alter in dem sich sprachspezifische Phonem-Repräsentationen anfangen zu etablieren. Im Schulalter wurden ebenfalls auditive Sprachverarbeitungsunterschiede zwischen Kindern mit und ohne SP beobachtet, was den Zusammenhang zwischen Schriftsprache und auditiven Sprachfähigkeiten bestätigt. Bezüglich visueller Sprachverarbeitung zeigte sich, dass beide Gruppen visuelle Sprachreize verarbeiten, wobei Kinder ohne SP eine typisch posterior verteilte Aktivierung aufwiesen. Im Gegensatz dazu zeigten Kinder mit SP eine stärker anterior verteilte Aktivierung, die normalerweise bei der Verarbeitung von auditiven Sprachreizen beobachtet wird und bedeuten könnte, dass Kinder mit SP versuchen ihr auditives Sprachverarbeitungsdefizit zu kompensieren. In einer weiteren Studie konnte gezeigt werden, dass Kinder mit SP Defizite bei der Integration visueller und auditiver Sprachinformationen aufweisen. Kinder, die jedoch stärker das auditive Sprachverarbeitungsdefizit durch die Nutzung von visuellen Sprachinformationen zu kompensieren versuchten,

zeigten eine annähernd normale Integrationsleistung. Es lässt sich schlussfolgern, dass Sprachverarbeitung nicht nur monosensorisch sondern multisensorisch betrachtet werden sollte, insbesondere bei der Erforschung zugrundeliegender Ursachen von schriftsprachlichen Defiziten. Es sollten dementsprechend nicht nur die Fähigkeiten zur auditiven Sprachverarbeitung bei Vorschülern mit dem Risiko zur Entwicklung schriftsprachlicher Schwierigkeiten und Kindern mit schriftsprachlichen Schwierigkeiten trainiert werden. Genauso wichtig sollte das Training zur visuellen Sprachverarbeitung und zur Integration visueller und auditiver Sprachinformationen sein.

Summary

Successful literacy acquisition requires auditory speech processing, visual processing, and the integration of visual and auditory information. Individuals with impaired literacy were found to exhibit deficient auditory speech processing, while their visual speech processing is not well understood. The current research project was designed to analyze when in development auditory speech processing starts to become predictive for later literacy acquisition, and to analyze, next to auditory, also visual and visual-auditory speech processing in school children with impaired literacy, here defined as writing problems (WP). We analyzed the event-related potential Mismatch Response in response to auditorily presented syllables at infant age and to syllables that were either presented auditorily, visually, or visual-auditorily at school age. We observed auditory processing differences between infants with and without later WP starting to develop at age 5 months—an age when normally developing infants begin to establish language-specific phoneme representations. At school age, these children with and without WP also showed auditory processing differences, confirming a relationship between literacy and auditory speech processing. Concerning visual speech processing, we found that both groups of children showed processing of visual speech stimuli, but with different scalp distribution. Children without WP showed a typical posterior distribution. In contrast, children with WP showed an anterior distribution. As anterior scalp distributions are typically reported for auditory speech processing, it could be suggested that children with WP try to compensate for their deficient auditory speech processing. In a further study, we found deficits in children with WP while integrating visual and auditory speech information. However, when children show strong attempts to compensate deficient auditory speech processing by relying on visual information, integration abilities in children with WP were found to be close to normal. The combined results of all three studies confirm that speech processing should not be interpreted as a monosensory phenomenon, but rather as a multisensory phenomenon, es-

pecially when investigating the underlying causes of impaired literacy acquisition. Overall, we suggest to not only train auditory speech processing, but also visual speech processing and visual-auditory speech integration in children with, and preschoolers at risk of, impaired literacy.

1 Introduction

1.1 Developmental Dyslexia

According to the Diagnostic and Statistical Manual of Mental Disorders: DSM-V (American Psychiatric Association, 2013), reading and writing[1] impairments belong to the category of specific learning disorders. In the following, reading and writing impairments will be referred to as developmental dyslexia (DD). DD is a neurodevelopmental disorder with biological origin, including an interaction of genetic, epigenetic, and environmental factors (Carrion-Castillo, Franke, & Fisher, 2013; Scerri & Schulte-Körne, 2010), affecting the brain's ability to perceive or process verbal or non-verbal information efficiently (American Psychiatric Association, 2013). It is one of the most common childhood disorders (4–5% of German school children are affected) that continues into adulthood (Schulte-Körne & Remschmidt, 2003).

As two of the most important cultural abilities, reading and writing are fundamental for knowledge acquisition. Thus, individuals with DD graduate below average (Esser, Wyschkon, & Schmidt, 2002) and their employment career is negatively affected (Schulte-Körne & Remschmidt, 2003), leading to higher unemployment (Esser et al., 2002). These findings specifically point towards the importance of investigating DD. The underlying causes and precursor symptoms need to be understood and recognized in order to diagnose the risk for DD in preschoolers and to be able to supply these individuals with compensational training programs.

1.2 Theories Concerning the Underlying Causes of Developmental Dyslexia

In the past decades a lot of researchers have focused on investigating DD in order to understand the underlying causes of reading and writing difficulties. Although

[1] *Note*: Here and in the following, writing refers to spelling, that is, the ability to express words by letters.

knowledge concerning DD increases, we still do not understand all underlying processes necessary for learning to read and write. Vellutino, Fletcher, Snowling, and Scanlon (2004) formulated a model depicting the different cognitive abilities and kinds of knowledge required for learning to read and consequently to write (see Figure 1).

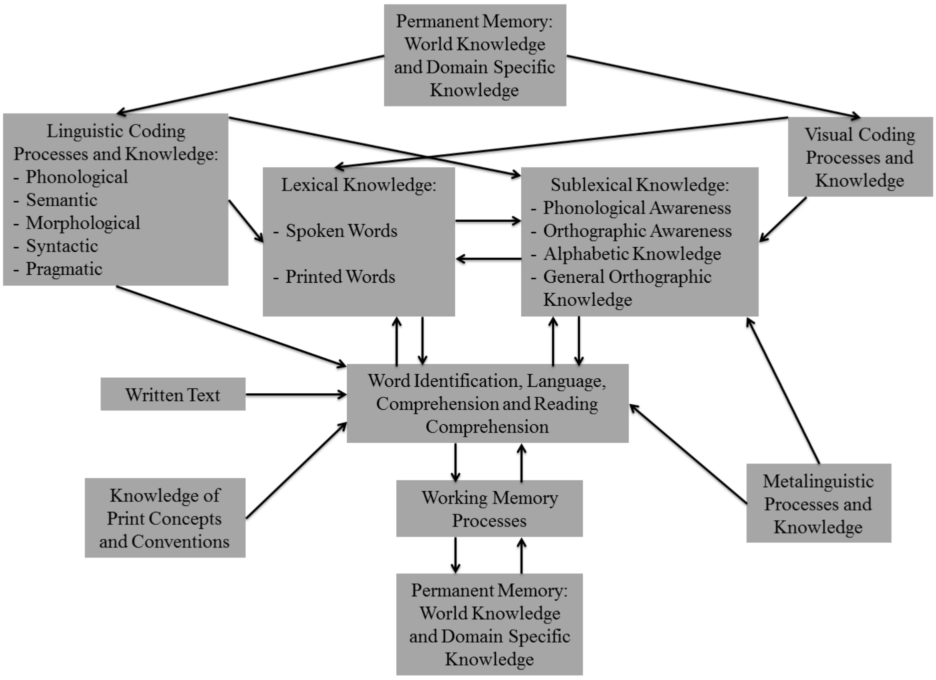

Figure 1. Cognitive processes and different types of knowledge involved in learning to read. Reprinted from "Specific reading disability (dyslexia): what have we learned in the past four decades" by F. R. Vellutino, J. M. Fletcher, M. J. Snowling, and D. M. Scanlon, 2004, *Journal of Child Psychology and Psychiatry, 45,* p. 4. Copyright 2004 by Blackwell Publishing.

For the acquisition of spoken and written language, world knowledge and domain specific knowledge are required, which are derived from linguistic processes, knowledge to acquire language skills, visual, linguistic, and metalinguistic processes. Visual coding processes enable the storage of representations, like graphic symbols that are used to represent written words. Linguistic coding enables language acquisition and the use of language for coding, storing, and retrieving information. Linguistic coding consists of semantic, morphological, syntactic, and pragmatic coding. Further, phonological coding is involved, which is the ability to use speech codes to represent information in the form of words and word parts. Before actual reading and writing abilities are acquired, linguistic and visual coding processes support children's development of sight word vocabulary—the ability to identify a number of printed words on sight as lexical, meaningful units. This associative learning process depends on the child's general understanding of print concepts and conventions (i.e., that written words represent words in spoken language, that they are processed from left to right, etc.). Due to a high degree of similarity between words derived from an alphabet (e.g., pot/top), visual memory is highly demanded during sight word learning. Visual memory demands are supported by general understanding and functional use of the alphabetic principal, which leads to phonological (letter-sound) decoding proficiency. Phonological decoding proficiency requires the engagement in metalinguistic analyses of language structures, which helps to gain sublexical knowledge on the basic level of letters. Within sublexical knowledge, phonological awareness can be described as the sensitivity to the sound structure of one's language (Wagner & Trogensen, 1987) and it is important for learning letter-speech sound correspondences (alphabetic knowledge). Furthermore, orthographic awareness refers to the knowledge of how letters are organized in written words and, together with phonological awareness, enables the child to acquire general orthographic knowledge—knowledge about regularities of an alphabetic writing system. In addition, long-term memory and working memory are involved for establishing connections between lexical and sublexical components of spoken and printed words, and for encoding, storing, and retrieving different types of information important for learning to read and write (Vellutino et al., 2004).

The highly complex acquisition of skills and subskills important for literacy acquisition depends on the normal development of the above described processes. Dysfunctions in one or more of these sub-systems and processes, influenced by genetic causes, and environmental and instructional experiences, lead to difficulties in literacy acquisition (see Vellutino et al., 2004), suggesting DD to be a diverse disorder. Accordingly, different subtypes characterized by different underlying deficits are discussed (e.g., Schulte-Körne & Bruder, 2010) and there are at least two large bodies of theories trying to explain DD. The first one concerns phonological coding, involving deficient phonological awareness, auditory processing, and alphabetic coding—the acquisition of the correspondence between letters and speech sounds. The second one concerns visual coding processes. I will describe the most discussed theories and findings concerning phonological abilities, visual coding processes, and acquisition of letter-speech sound correspondences, namely crossmodal integration deficits, in the following.

1.2.1 Phonological Processing Deficits

The *phonological theory*, as one of the most widely accepted views regarding the development of DD, postulates reading and writing difficulties to be caused by a cognitive deficit specific to representations and processing of speech sounds (Snowling, 1998). Accordingly, the most consistently reported difficulties in children with reading and writing impairments concern phonological awareness abilities and phonological working memory capacities during, for example, nonword repetition (e.g., Baddeley, 2003; Baddeley & Wilson, 1993; Snowling, 1998). Phonological awareness has been discussed as one of the main abilities for success in learning to read and write, and preschool phonological awareness abilities were shown to serve as one of the best predictors for later literacy acquisition (Mann & Liberman, 1984; Moll et al., 2014; Snowling, 1998).

Other researchers generally agree with the *phonological theory*, but discuss the phonological deficit as a secondary impairment caused by a more basic low-level auditory processing deficit. The *auditory processing deficit theory* postulates individuals with DD to suffer from a basic, non-linguistic deficit in temporal resolution of rapidly changing auditory stimuli that impairs speech perception as a consequence (Tallal, Miller, & Fitch, 1993). Interestingly, it has been shown that temporal acoustic cues embedded in both non-speech and speech stimuli are processed in the same network within left superior temporal areas (Zaehle, Wustenberg, Meyer, & Jancke, 2004). Furthermore, the *attentional sluggishness theory* postulates an attention-related deficit during the processing of rapid auditory stimulus sequences, such that less information can be stored in input chunks, leading to an improper development of cortical representations relevant for literacy acquisition (Hari & Renvall, 2001; Lallier et al., 2009).

Generally, it was demonstrated that the phonological deficit of individuals with DD can arise in the absence of any auditory disorder, yet with the most severe auditory impairments acting as aggravating factors (see also Ramus et al., 2003). In line, auditory phoneme discrimination, as an essential feature of phonological awareness skills (Jansen & Marx, 1999), was found to be deficient in German children and adults with DD, but not the discrimination of simple sounds (Paul, Bott, Heim, Wienbruch, & Elbert, 2006; Schulte-Körne, Deimel, Bartling, & Remschmidt, 1998, 2001). Additionally, there is evidence for deficits in the discrimination of phoneme duration changes (Corbera, Escera, & Artigas, 2006) and phoneme, phoneme duration, and intensity changes (Lovio, Näätänen, & Kujala, 2010), pointing towards widespread phonological difficulties in individuals with DD.

Speech perception is, however, not only an auditory process: visual speech information is crucially involved (Benoît, Guiard-Marigny, Goff, & Adjoudani, 1996). As far as is known, there are no theories concerning visual speech processing, but theories on general visual processing deficits in individuals with DD.

1.2.2 Visual Processing Deficits

The *magnocellular visual deficit theory* postulates visual processing deficits in individuals with DD, depending on neurodevelopmental abnormalities of the visual magnocellular system (Stein, 2001; Stein & Walsh, 1997), which normally supports the processing of rapidly moving visual stimuli. Especially, visual motion detection is thought to be important for perceiving the word-form and position of letters in words (Demb, Boynton, Best, & Heeger, 1998).

Accordingly, individuals with DD show deficient visual motion detection and reduced visual speed discrimination (Heim et al., 2010; Meng, Cheng-Lai, Zeng, Stein, & Zhou, 2011; Talcott et al., 2003). Interestingly, magnocellular neurons that are specialized for temporal processing are found throughout the whole brain (Hockfield & Sur, 1990). Thus, Stein (2001) concluded that both visual processing deficits and auditory processing deficits in individuals with DD are caused by affected magnocells in general.

Eye-movements are necessary for perceiving words, and the *visual tracking theory* postulates that deficient eye-movements cause DD. During reading, individuals with DD were found to fixate longer, execute more regressions, and show shorter saccades (Stark, Giveen, & Terdiman, 1991). However, this theory has been discussed controversially. Olson, Rack, and Conners (1991) did not find any visual processing differences between individuals with and without DD when reading abilities of the control group were paralleled, suggesting the development of deficient eye-movements to depend on literacy acquisition itself.

Next to phonological abilities and visual coding, alphabetic coding is necessary for the acquisition of reading and writing, which highly depends on the former two processes. For learning letter-speech sound correspondences, graphemes, namely letters, need to be visually encoded, phonemes, namely speech sounds, need to be phonologically encoded, and corresponding units need to be identified, crossmodally integrated, and memorized (Perfetti, 1999).

1.2.3 Crossmodal Integration Deficits

Crossmodal integration can be described as the ability to integrate information of different sensory modalities, such as visual and auditory information. Birch and Belmont (1964)'s study was one of the first demonstrating visual-auditory integration to be highly important for literacy acquisition. They argued that temporally distributed auditory patterns, namely phonemes that are strung together, must be matched onto spatially distributed visual patterns, namely graphemes that are strung together, and vice versa. More specifically, Vellutino (1987) differentiated between verbal and non-verbal crossmodal integration tasks and found individuals with DD to only show deficient integration of graphemes and phonemes—the verbal task (see also Ehri, 2005).

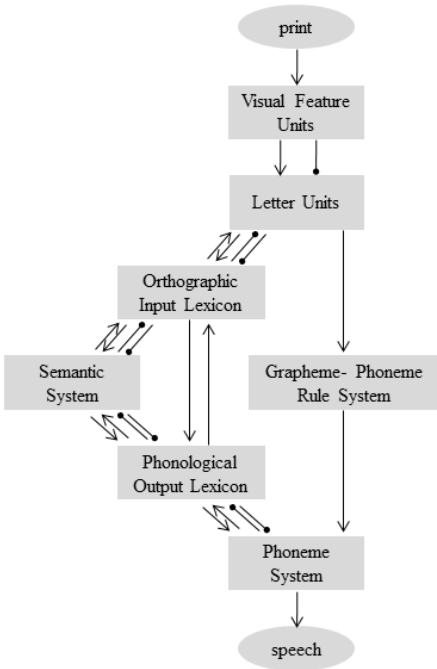

Figure 2. Dual-route cascaded model of visual word recognition and reading aloud (DRC-model). Reprinted from "DRC: A Dual Route Cascaded Model of Visual Word Recognition and Reading Aloud," by M. Coltheart, K. Rastle, and C. Perry, 2001, *Psychological Review, 108,* p. 214. Copyright 2001 by the APA.

One model depicting the importance of the integration of visually represented graphemes and auditorily represented phonemes, and the memorization of corresponding letter-speech sound units for literacy acquisition is the *dual-route-cascaded model* (DRC-model). The model describes three different routes between the perception of print and reading out loud (see Figure 2, Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). On the one hand, a familiar word activates the lexical routes (left part of Figure 2), either via the semantic system (i.e., lexical-semantic route) or not (i.e., lexical non-semantic route). On the other hand, unfamiliar words, which most words are for children beginning literacy acquisition, activate the slower, non-lexical route, where each orthographic unit is connected to a phonological unit sequentially (right part of Figure 2). Here, the grapheme-phoneme-rule system supports the connection and integration of corresponding orthographic and phonological units (i.e., crossmodal integration), which was found to be deficient in individuals with DD (Blau et al., 2010; Blau, van Atteveldt, Ekkebus, Goebel, & Blomert, 2009).

However, most recent studies concerning crossmodal integration in individuals with DD have solely concentrated on the integration of letters and speech sounds Thus, it is difficult to differentiate between general deficient verbal crossmodal integration, independent of letter knowledge, and deficient integration of letter-speech sound pairs due to unsuccessful literacy acquisition itself.

1.3 The Diagnosis of Developmental Dyslexia

As described, the knowledge concerning the underlying causes of DD has tremendously increased. Despite this, children with DD are not diagnosed until they actually start literacy acquisition. DD-diagnosis is realized by psychometric tests at the end of the 2nd grade (at an age of 7 years in Germany), when language development is almost completed. For example, the German Writing Test (DERET; Stock & Schneider, 2008) and the Reading Comprehension Test for first to sixth graders (ELFE 1-6; Lenhard & Schneider, 2006) are applied. One psychometric test, which can already be applied 10 months before school enrollment, is the Bielefeld Screening for the early recognition of reading and writing problems (BISC; Jansen, Mannhaupt, Marx, & Skowronek, 2002). The BISC tests prerequisites for literacy acquisition, namely working memory, attention being a part of working memory (i.e., the central executive; Baddeley, 2003), and phonological awareness. However, successful therapy highly relies on the early onset of therapeutic and supportive measures to effectively influence the learning process, so for this purpose 10 months might still be insufficient.

Auditory discrimination, essential for phonological awareness skills (Jansen & Marx, 1999), was found to develop early in life (Friederici, Friedrich, & Weber, 2002) and it can be investigated by a characteristic event-related brain potential (ERP) component called Mismatch Response (MMR, for detailed description, see 3.3). In DD, Schulte-Körne and colleagues (Schulte-Körne et al., 1998, 2001) found a significantly reduced negative MMR amplitude in German school children and adults with DD in response to speech sounds. Furthermore, specific characteristics of the MMR led researchers to hope that it might be used as a diagnostic tool for the early risk diagnosis of DD, starting at an earlier age than the BISC can be applied. These characteristics are objectivity (for review, see Näätänen, 1995), independency of attention (Näätänen, Paavilainen, Tiitinen, Djiang, & Alho, 1993), and suitability for investigating auditory discrimination in infants (Molfese, 1997). Consequently, the MMR has been investigated in infants at risk of developing DD, which was defined by at least one parent with diagnosed DD. Pihko et al. (1999) found differences between the MMR of at risk and not at risk infants in response to short and long vowels (/ka/ vs. /kaa/) in 6-month-old infants, but not in newborns. Confirming these results, Leppänen et al. (2002) demonstrated different MMR responses of 6-month-old infants at risk compared to infants not at risk in response to varying /t/ durations in the pseudoword /ata/ (Leppänen et al., 2002). Thus, differences between infants at risk and not at risk of developing DD start to appear during the first six months of life, which has also been reported to be a time window when the MMR starts to become language-specific (Cheour et al., 1998; Friederici, Friedrich, & Christophe, 2007). Further supporting the hope for using the MMR as a diagnostic tool are associations between the MMR amplitude and DD candidate genes, such as KIAA0319 (Czamara et al., 2011). However, DD is not only genetically

(Scerri & Schulte-Körne, 2010), but also environmentally, that is, parental influence and schooling experience (Samuelson & Lundberg, 2003), shaped. Thus, risk studies cannot analyze the direct link between DD at school age and infants' auditory discrimination capacities. Rather, studies are needed that are able to retrospectively investigate auditory speech discrimination capacities, as one of the abilities predicting success in literacy acquisition (Snowling, 1998), in infancy of diagnosed children, which was one aim of the current research project.

2 Research Questions and Hypotheses

As described in the introduction, phonological, but also visual, processing abilities and the ability to integrate visual and auditory information are predictive for successful literacy acquisition. The current research project was designed to analyze auditory, visual, and visual-auditory speech processing in school children with writing problems (WP)[2].

The amplitude of the MMR was found to be associated with reading and writing abilities and the risk of developing DD: Children with DD, and infants at risk of developing DD, show a reduced negative MMR in response to speech stimuli (Leppänen et al., 2002; Schulte-Körne et al., 1998). Additionally, certain characteristics of the MMR led researchers to hope that it might be used as an early diagnostic tool (see also Bishop, 2007). However, the relationship between infants' discrimination capacities and later DD needs to be analyzed directly, by applying a retrospective longitudinal approach, in order to analyze the predictive power of the infants' MMR for later DD. Thus, we addressed the following main question:

- At which age do auditory speech discrimination differences develop between German infants with and without later diagnosed WP, and can the MMR be used for diagnostic purposes at an early age?

Hypothesis I.a: We expected group differences between infants with and without later WP at age 5 months, the time point when MMR starts to become language-specific (Cheour et al., 1998; Friederici et al., 2007), reflected in attenuated MMR amplitudes in infants with later WP in response to natural speech stimuli compared to infants without later WP.

Hypothesis I.b: We did not expect MMR amplitude differences between infants with and without later WP at age 1 month.

[2] *Note*: Writing refers to the spelling abilities of the children.

Hypothesis I.c: Further, in line with previous studies, we expected to confirm group difference between school children with and without WP, reflected in attenuated MMR amplitudes in children with WP in response to natural speech stimuli compared to children without WP.

However, speech processing is a multisensory phenomenon with visual speech information being crucially involved (Benoît et al., 1996). For perceiving visual speech information, visual motion processing is important (for a review see Campbell, 2008), which was found to be deficient in individuals with DD in response to non-linguistic symbols. Furthermore, it was demonstrated that children and adults with DD show reduced lip-reading abilities compared to their normally developing peers (de Gelder & Vroomen, 1998; Mohammed, Campbell, Macsweeney, Barry, & Coleman, 2006). As far as is known, visual speech processing in the ERP has not been investigated in relation to DD. Therefore, we addressed the following main question:

- Is visual speech processing, like auditory speech processing, impaired in school children with WP due to their deficient visual motion processing probably leading to reduced lip-reading abilities?

Hypothesis II: We expected group differences between school children with and without WP during visual speech discrimination, reflected in attenuated visual MMR amplitude in response to visual speech stimuli in children with WP compared to children without WP, due to their deficient visual motion processing.

Recent studies concerning deficient crossmodal integration in individuals with DD have mostly concentrated on letter-speech sound integration. Given the evidence that both first-graders and 11-year-old children with DD show difficulties in processing letter-speech sound pairs (Froyen, Bonte, Van Atteveldt, & Blomert, 2009; Froyen, Willems, & Blomert, 2011), it is difficult to infer the underlying deficit: School children could either suffer from a visual-auditory speech integration deficit originating from early developmental stages (e.g., integration of mouth-movements and corresponding speech sounds) or deficient letter-speech sound integration typically occurring during literacy acquisition. The assessment of school children's ability to process visual-auditory speech information (i.e., mouth movement and corresponding speech sounds) can deliver insight into crossmodal integration abilities relatively independent of literacy knowledge, as the combined processing of visual and auditory speech information requires the ability to crossmodally integrate (van Wassenhove, Grant, & Poeppel, 2005).

Therefore, we addressed the following main question:

- Do school children with WP exhibit a general verbal crossmodal integration deficit during visual-auditory speech processing?

Hypothesis III.a: If we find a reduced visual-auditory MMR in children with WP compared to children without writing problems, results would point to an early acquired visual-auditory speech integration deficit, since our experimental manipulation is more independent of letter-sound knowledge, gained during literacy acquisition, than studies using letter-speech sound pairs as stimuli (e.g., Froyen et al., 2011).

Hypothesis III.b: If we do not find visual-auditory MMR differences between children with and without writing problems, results would point to intact visual-auditory speech integration, when tested independently of letter knowledge.

3 General Methodological Approach

3.1 Participants

Children were participants of a longitudinal study (German Language Developmental Study) starting at children's birth. At preschool age, the BISC (Jansen et al., 2002) was applied for assessment of phonological awareness abilities and the risk of later DD. From the original 198 participants of the GLAD-Study, we could invite 33 children at risk of developing later reading and spelling problems. Accordingly, for our control group, we invited 34 children that were not at risk of developing later reading and spelling problems. These children were tested individually with the DERET (Stock & Schneider, 2008) at the age of 9.5 years (grade 3 or 4). Children were classified based on the risk diagnosis (BISC; Jansen et al., 2002) at preschool age and their writing abilities at school age (DERET; Stock, & Schneider, 2008). In German children, writing abilities are often used for classification (see also Neuhoff et al., 2012), as grapheme-phoneme correspondences are consistent, fostering reading skills, but phoneme-grapheme correspondences are less consistent, hindering writing skills, which leads to more persistent writing impairments compared to reading impairments (Landerl & Wimmer, 2008).

Children at risk of developing DD and with a percentile rank (PR) < 25 in the writing test were classified as children with WP (*N*=17). Children not at risk of developing DD and with a PR > 25 in the writing test were classified as children without WP (*N*=21)[3]. For these 38 children (mean age = 9.64 years; SD = 0.43), audiometric responses to sounds of varying frequencies (i.e., 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz) and intensities (Decibel Sound Pressure Level; dB SPL) were determined in a sound-attenuated cabin. No child was below the critical threshold of 25 dB SPL in any frequency. For vision, parents were asked about children's eyesight. All children that were either myopic or hyperopic wore

[3] *Note*: Two children without WP and one child with WP did not participate in Study II and Study III.

glasses for compensation. Further, the Reading Speed and Comprehension test for grade 6-12 (LGVT 6-12; Schneider, Schlagmüller, & Ennemoser, 2007), a reading test by Schulte-Körne (2001) for measuring reading speed and accuracy, the Test for Basic Competences for Reading and Writing (BAKO; Stock, Marx, & Schneider, 2003) for assessment of phonological awareness abilities at school age, and the German version of the Kaufmann-Assessment Battery for Children (K-ABC; Kaufman, Kaufman, Melchers, & Preuß, 2009) for assessment of non-verbal intelligence were conducted. At school age, groups did not differ significantly in their nonverbal intelligence and reading comprehension and accuracy, but in their reading speed and phonological awareness abilities. All children had previously been tested on their auditory discrimination abilities at age 1 month (+/– 2 days) and at age 5 months (+/– 2 days) (see Quandt, 2004).

The studies followed American Psychological Association (APA) standards in accordance with the declaration of Helsinki (World Medical Association, 2013) and were approved by the responsible ethics committees (i.e., University of Leipzig for school children data; Charité – Universitätsmedizin Berlin for infant data (see Study I)). Parents of participating children were reimbursed (€ 7.00 per hour).

3.2 Electroencephalography and Event-Related Potentials

Electroencephalography (EEG) was the method of choice for analyzing visual, auditory, and visual-auditory speech processing in school children with and without WP.

The EEG reflects brain activity on the millisecond level through recording ongoing voltage fluctuations at scalp level (Rugg & Coles, 1995). As the effect from a single stimulation is only a small part of the ongoing brain activity, the part associated with the event at interest needs to be extracted. Repeated stimulation with pre-defined stimuli and averaging across those epochs of the EEG generates a stable event-related potential (ERP; Birbaumer & Schmidt, 2006). ERPs in response to different stimuli can be statistically compared. Their difference can give information about the strength of the involved neurophysiological process underlying the cognitive process associated with the event (i.e., stimulus) of interest (Kutas, van Petten, & Kluender, 2005).

For reliable ERPs, the raw EEG needs to be preprocessed as it is prone to noise (e.g., electric streams stemming from muscle activity). For example, muscle activity needs to be removed from the EEG as it is larger in magnitude than ERPs and consequently leads to spurious ERPs. For identification and removal of artifacts, various techniques are available, such as filtering for muscle activity (Edgar, Stewart, & Miller, 2005).

3.3 Oddball Paradigm and Mismatch Response

The oddball paradigm is one of the most suitable paradigms for gaining stable ERPs as it adequately fulfills the need for repetitive presentation of stimuli. Squires, Squires, and Hillyard (1975) were the first to apply the oddball paradigm to measure ERPs. During an oddball paradigm, an auditory or visual stimulus is repetitively presented (i.e., standard) and gets occasionally replaced by a differing stimulus (i.e., deviant). When comparing the response to the deviant with the response to the standard stimulus, an ERP called MMR can be observed (Näätänen, Gaillard, & Mäntysalo, 1978). Oddball paradigms can be active, when participants respond to the deviant stimulus, or passive, when participants experience a series of stimuli without a behavioral response.

The MMR in response to auditory stimuli (aMMR) is an anteriorly evoked negativity at about 100–200 ms after stimulus onset of a deviant stimulus during a passive oddball paradigm, and was first discovered by Näätänen et al. (1978). The aMMR has been found to be elicited in reactions to a wide range of auditory stimulus-types and, most importantly, in response to speech stimuli, such as syllables (for a review, see Näätänen, Paavilainen, Rinne, & Alho, 2007). Furthermore, the aMMR is thought to be relatively independent of conscious attention

(Näätänen et al., 1993), making it suitable for investigating auditory discrimination in infants (Friederici et al., 2002). Equivalently, the visual MMR (vMMR) was found to occur in response to deviant visual stimuli (i.e., nonlinguistic, visually presented symbols; Czigler, Weisz, & Winkler, 2006), and visual speech stimuli, like mouth movements (Files, Auer, & Bernstein, 2013). The vMMR was found to be located in supplementary visual areas in the occipital and posterior temporal cortex. Finally, there is also evidence for a visual-auditory mismatch response (vaMMR) in response to deviant visual-auditory speech stimuli, like mouth movements and corresponding speech sounds (Ponton, Bernstein, & Auer, 2009). The vaMMR can be located in lateral temporal cortices, such as the superior temporal gyrus (STG) and superior temporal sulcus (STS; Ponton et al., 2009), also associated with letter-speech sound integration (van Atteveldt, Formisano, Goebel, & Blomert, 2004). In contrast to the aMMR, stimuli need to be focused visually for the elicitation of the vMMR and the vaMMR. Taken together, the MMR is suitable for investigating auditory, visual, and visual-auditory speech processing, which was the aim of the current dissertation project.

3.4 Paradigm and Stimuli for this Research Project

For investigating auditory, visual, and visual-auditory speech processing in school children with and without WP, we conducted a passive oddball paradigm with three different experimental variations. For all three experiments the syllables /pa/ and /ga/ were used and were kept as natural as possible. The phonemes /p/ and /g/ were chosen, because they contribute to the difference in meaning in German words (e.g., /p/latt vs. /g/latt; /P/aten vs. /G/a[r]ten) and they can be discriminated both auditorily and visually.

Mouth movements of a female German actress were video-recorded (for visual stimulation) and speech sounds were audiotaped (for auditory stimulation) simultaneously. A design with two blocks was used to control for physical differences between stimuli. The syllable /ga/ was used as a standard and the syllable /pa/ as a deviant in one block; and vice versa in the other block. By this, the syllable /pa/ could be compared as a deviant with itself as a standard, and likewise the syllable /ga/. The order of the blocks was counterbalanced across children and experiments. For all experiments, one block consisted of 600 stimuli, with 85% standard and 15% deviant stimuli. The presentation of the deviants was pseudo-randomized, such that at least two standards were presented in between the deviants. For auditory speech discrimination (Study I) the syllable /pa/ was 266 ms and the syllable /ga/ 409 ms in length. Due to the different length of the syllables, the inter-stimulus-interval (ISI) varied between 1450 and 1750 ms. For visual speech discrimination (Study II) the mouth movements pronouncing syllables silently were both 1.440 ms in length and the ISI between two syllables (offset to onset) was 500 ms. For visual-auditory speech discrimination (Study III), both stimuli lasted for 1440 ms. For /pa/ the mouth movement started 200 ms after stimulus onset and lasted for 1160 ms. The sound started 580 ms after stimulus onset and lasted for 266 ms. For /ga/ the mouth movement started 80 ms after stimulus onset and lasted for 1280 ms. The sound started 320 ms after stimulus onset and lasted 409 ms. The ISI between two syllables (offset to onset) was 500 ms (for illustration, see Figure 3).

Visual stimulation was realized via a 15-inch monitor (display resolution: 1024 x 768). The distance between the children and the monitor was controlled for and measured 75 cm.

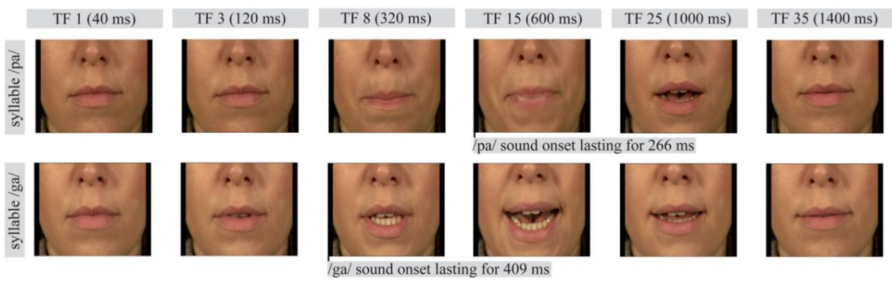

Figure 3. Illustration of stimuli used for investigating auditory, visual, and visual-auditory speech discrimination. Here, only representative time frames (TF) of video recorded mouth movements are presented.

Auditory stimulation was realized binaurally via loud speakers with an intensity of 64 dB SPL. For the visual and visual-auditory experiment, children were instructed to watch the mouth-movements. Further, an independent observer monitored each child online during the experiment. At the end of each experimental block the observer rated the attention directed towards the stimuli (in percent). During the auditory speech discrimination experiment at school age (Study I), children watched a silent video of “the mole”, a Czech children’s cartoon, on a small video screen placed in front of them to prevent extreme eye movements and boredom. Each experiment lasted for 45 min and the whole procedure for one experiment lasted for about 90 min.

For auditory speech discrimination tested at infant age (Study I) the syllables /da/ and /ga/ were used. As both syllables were 150 ms in length and to reduce exhaustion for infant participants, all participants received only one block with the syllable /da/ as the standard and /ga/ as the deviant. In total 600 syllables, with 500 standards (83%) and 100 deviant syllables (17%), were presented. The ISI between two syllables was 750 ms. The experiment lasted for 10 min and the whole procedure lasted for about 90 min (see Quandt, 2004).

4 Summaries of the Three Experimental Studies

4.1 Study I "Present and past: Can writing abilities in school children be associated with their auditory discrimination capacities in infancy?"

4.1.1 Background

Study I examines the relationship between auditory speech discrimination in response to natural syllables and writing abilities at school age, and determines the time-point when auditory speech discrimination differences, relevant for later writing abilities, start to develop in infancy.

Schulte-Körne et al. (1998) demonstrated a diminished negative aMMR in German school children with DD compared to their normally developing peers in response to speech stimuli, but not in response to simple sounds. Furthermore, infants at risk of developing DD show reduced auditory discrimination capacities, namely a diminished aMMR compared to infants not at risk of developing DD, at age 6 months (Leppänen et al., 2002).

However, auditory discrimination capacities in infancy and later DD should be investigated by applying a retrospective approach in order to analyze the association between early auditory discrimination capacities and later writing abilities directly. Here, we investigated the aMMR in response to natural syllables (see also, Shestakova et al., 2002) in German school children with and without WP, and, by applying a retrospective approach, in these children when they were 1 month and 5 months old. By this we aimed to determine the time-point in development when differences in speech discrimination abilities relevant for successful writing acquisition emerge.

4.1.2 Methods

A passive auditory oddball paradigm was conducted to analyze auditory speech discrimination in children with and without WP at school age and infant age (for description see 3.).

Mixed-model design analyses of variance (ANOVAs) were performed for the three different age groups. To test for a significant aMMR, we compared the ERPs for standard stimuli with the ERPs for deviant stimuli ($p \leq .05$). Writing abilities (with, without WP) were included as between-subject factor. Analyses were computed on a frontal region of interest (ROI) (F3, FZ, F4), a central ROI (C3, CZ, C4), and a parietal ROI (P3, PZ, P4). ROIs were defined due to electrode settings of the infant data acquisition and typically found fronto-central distribution effects of the aMMR (e.g., Näätänen, Paavilainen, Rinne, & Alho, 2007).

4.1.3 Results

Figure 4 illustrates the aMMR of school children with and without WP. At school age, ERP measures revealed significant differences between the aMMR of children with and without WP in response to natural syllables. For the syllable /pa/, school children with WP showed a positive aMMR and school children without WP a negative aMMR. In response to /ga/, both groups showed a positive aMMR. Effect sizes (η_p^2) demonstrated quantitative discrimination differences for /ga/, namely a less pronounced positive aMMR in school children without compared to school children with WP.

Figure 4 illustrates the aMMR for infants with and without later WP at 1 month and 5 months. ERP measures revealed no significant differences between the aMMR of 1-month-old infants, but between the aMMR of 5-month-old infants with and without later WP. Five-month-old infants without later WP showed a significant frontal negative aMMR in response to the deviant stimulus, but 5-month-old infants with later WP did not.

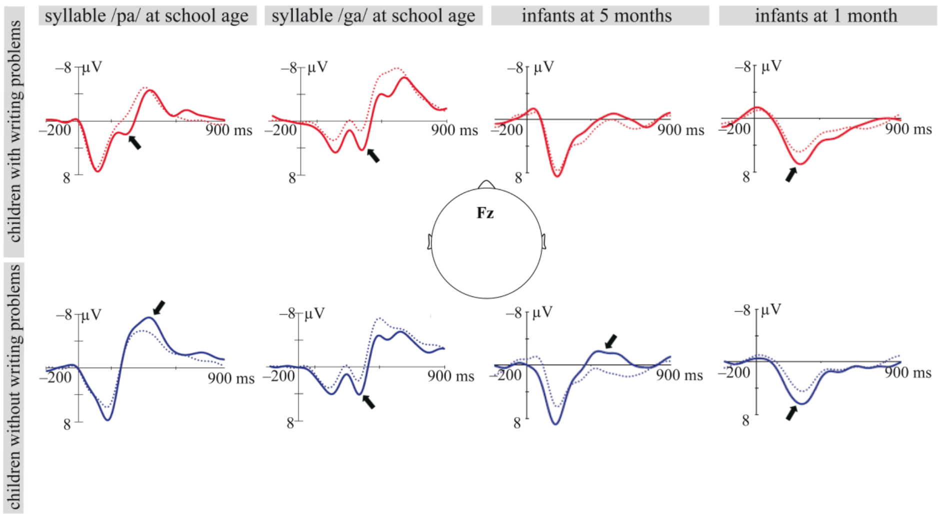

Figure 4. Figure adapted from Schaadt et al. (a, submitted). ERPs for standard stimuli (dotted line) and deviant stimuli (solid line) are presented separately for children with WP (top panel, red) and children without WP (bottom panel, blue). ERPs in response to the syllable /pa/ and to the syllable /ga/ at school age and ERPs at 5 months and 1 month are presented separately. Black arrows indicate significant aMMRs.

4.1.4 Discussion

The three experiments summarized here investigated the relationship between auditory speech discrimination at school age and infancy, and writing abilities at school age, by means of the aMMR. As expected (**Hypothesis 1.c**), we confirmed aMMR differences between children with and without WP at school age (Corbera et al., 2006; Kujala, Lovio, Lepistö, Laasonen, & Näätänen, 2006), specifically in response to natural syllables. Beyond this, we observed qualitative differences (i.e., different aMMR polarity) in response to the syllable /pa/ and quantitative differences (i.e., different aMMR amplitude) in response to the syllable /ga/ between children with and without WP. These differences concerning the response to the syllables /pa/ and /ga/ will be discussed in more detail in the general discussion (see 5.2.1).

Confirming our retrospective hypotheses, we found aMMR differences in response to natural syllables between infants with and without later diagnosed WP at the age of 5 months (**Hypothesis I.a**), but not at the age of 1 month (**Hypothesis I.b**). At age 5 months, infants without later WP are able to discriminate natural syllables, but infants with later WP are not. These developmental differences in auditory speech discrimination can be explained as language-specific phonemic representations of speech start to develop and the aMMR becomes language specific during infants' first five months of life (Cheour et al., 1998; Friederici et al., 2007). Thus, 5-month-old German infants without later WP have established long-term representations of speech more successfully than 5-month-old German infants with later WP.

4.2 Study II "Facial speech gestures: The relation between visual speech processing, phonological awareness, and spelling problems in 10-year-olds"

4.2.1 Background

Study II examines the relationship between visual speech discrimination and writing abilities at school age. Speech perception is a multisensory phenomenon, involving both auditory information and visual information (Benoît et al., 1996). Visual information, namely mouth movements, precedes auditory information during speech perception (Chandrasekaran, Trubanova, Stillittano, Caplier, & Ghazanfar, 2009). Accordingly, Arnal, Morillon, Kell, and Giraud (2009) demonstrated the brain's anticipation of auditory signals when being presented with visual signals. Thus, visual speech information might support speech processing in noisy environments (Bernstein, Auer, & Takayanagi, 2004), but also during clearly audible and intact speech (Arnold & Hill, 2001).

Equivalent to the aMMR, the vMMR can be used to investigate visual speech processing (Files, Auer, & Bernstein, 2013). Yet, in contrast to auditory speech processing, no equivalent studies investigated visual speech processing in individuals with DD, although visual speech processing plays an important role during speech development (Lewkowicz & Hansen-Tift, 2012). Furthermore, as described in the introduction, there are theories postulating visual processing deficits in individuals with DD (Stein, 2001). Therefore, the present study investigated the vMMR in response to visual speech stimuli in school children with and without WP.

4.2.2 Methods

A passive visual oddball paradigm was conducted to analyze visual speech discrimination in school children with and without WP (for description, see 3.).

Mixed-model design analyses of covariance (ANCOVAs) were performed. To test for a significant vMMR, we compared the ERPs for standard stimuli with the ERPs for deviant stimuli ($p \leq .05$). Writing abilities (with, without WP) were included as between-subject factor and attention (i.e., ratings of independent observer) and eye-movements (i.e., vertical and horizontal Electrooculograms; EOG) were added as covariates, as attention and differences in eye-movements could have an impact on potential group differences regarding the vMMR. Analyses were computed on a frontal region of interest (ROI) (F3, FZ, F4), a central ROI (C3, CZ, C4), and a parietal ROI (P3, PZ, P4). These ROIs were chosen due to typically found fronto-central distribution effects of the aMMR (e.g., Näätänen, Paavilainen, Rinne, & Alho, 2007) and the posterior distribution effects of the vMMR (Maekawa et al., 2005). Further, we calculated Pearson's bivariate correlation coefficient between the vMMR difference wave (deviant–standard) and writing abilities (PR of DERET), and between the vMMR and phonological awareness abilities for all ROIs separately for children with and without WP.

4.2.3 Results

Figure 5 illustrates the vMMR in response to mouth movements pronouncing syllables silently, separately for children with and without WP. Both groups show a significant vMMR. However, children with WP showed an anteriorly distributed positive vMMR, whereas children without WP showed a posteriorly distributed positive vMMR. These effects were not influenced by attention[4] or eye-movements as we did not find any significant interactions with afore mentioned covariates.

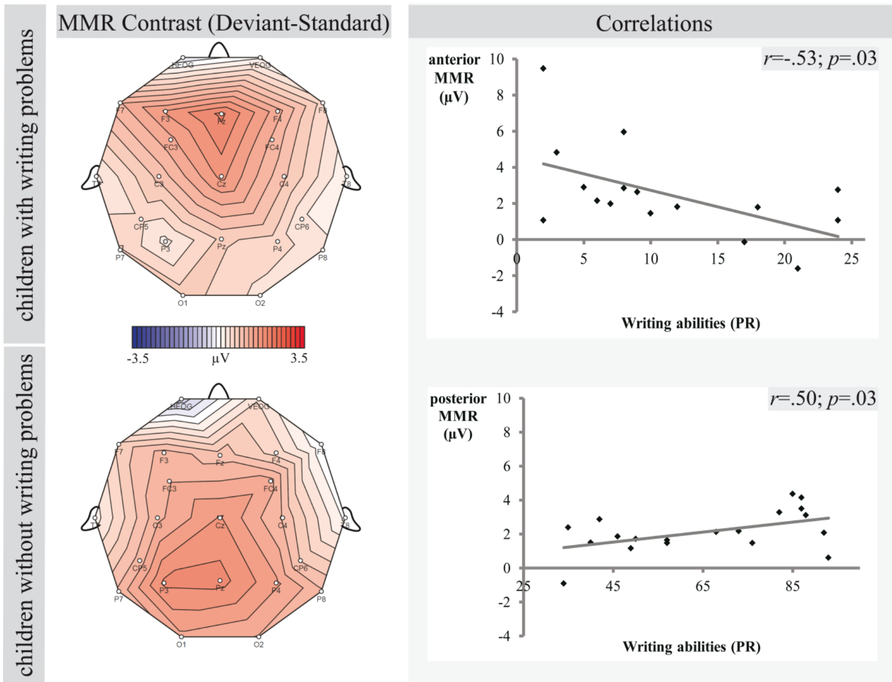

Figure 5. Figure adapted from Schaadt et al. (b, submitted). Topographic plots (left panel) show MMR difference wave (deviant–standard) for children with WP (top panel) and without WP (bottom panel) across both syllables (/pa/, /ga/) with no interactions involving condition and syllable-type. Right panel illustrates the relation between writing abilities and MMR difference wave.

Correlational analyses showed low writing abilities (PR) in children with WP to be associated with increased anterior vMMR amplitudes (see Figure 5), and low phonological awareness abilities (PR) in children with WP also to be associated with increased anterior vMMR amplitudes (r= –.52) . In children without

[4] *Note*. The measure of attention is suboptimal and should be considered carefully (for discussion, see 5.6).

WP, high writing abilities (PR) were found to be associated with increased posterior vMMR amplitudes (see Figure 5), but no association between phonological awareness and vMMR amplitudes were found.

4.2.4 Discussion

The experiment summarized here investigated the relationship between visual speech discrimination, phonological awareness, and writing abilities, by means of the vMMR in response to mouth movements pronouncing syllables silently. In contrast to our hypothesis (**Hypothesis II**), both groups of children showed a vMMR. However, we found distributional differences between children with and without WP during visual speech discrimination. Children without WP showed a positive vMMR with a posterior scalp distribution that was positively correlated with children's writing abilities, matching the typical distribution normally reported for the vMMR (Czigler et al., 2006; Files et al., 2013). In contrast, children with WP showed a long-lasting positive vMMR with a more anterior scalp distribution, normally observed for the aMMR (for a review, see Näätänen et al., 2007), and which was negatively correlated with children's writing abilities and phonological awareness. The anterior vMMR during visual speech processing in children with WP might be regarded as an anticipation of the potentially upcoming auditory signal (Arnal et al., 2009), normally following visual speech input (Chandrasekaran et al., 2009), possibly in an attempt to compensate for their phonological deficit (see 5.3 for further discussion).

4.3 Study III "Deficient visual-auditory speech processing in elementary school children with limited spelling abilities: When crossmodal integration goes wrong independent of letter knowledge"

4.3.1 Background

Study III was conducted to investigate the question whether school children with WP exhibit verbal crossmodal integration deficits during visual-auditory speech processing, independent of letter knowledge. Additionally, we were further able to analyze whether visual speech information can be used to successfully compensate for auditory speech discrimination deficits (see Study I) in school children with WP. As summarized in Study II, visual information processing is crucially involved during speech perception (Benoît et al., 1996) and supports speech processing in adults and infants (Arnold & Hill, 2001; Teinonen, Aslin, Alku, & Csibra, 2008). For visual speech information to be beneficial, visual and auditory speech information need to be crossmodally integrated. Although infants can already integrate visual and auditory information at age 10 months (Neil, Chee-Ruiter, Scheier, Lewkowicz, & Shimojo, 2006), children and adults with DD show crossmodal integration deficits (see also Introduction). Individuals with normal reading and writing abilities show an enhancement of the aMMR in response to deviant speech sounds, if the standard stimulus is bimodally presented, namely the speech sound and the corresponding letter (Froyen, Van Atteveldt, Bonte, & Blomert, 2008). However, integration of letter-speech sound pairs needs to develop during literacy acquisition (Froyen et al., 2009). Interestingly, 11-year-old children with DD do not benefit from bimodally presented letter-speech sound pairs, compared to their normally developing peers that show similar aMMR enhancement like adults (Froyen et al., 2009; Froyen et al., 2011). However, these results cannot differentiate between general deficient verbal integration in individuals with DD, independent of letter knowledge, and deficient integration of letter-speech sound pairs resulting from unsuccessful literacy acquisition. The present study investigated visual-auditory speech processing independent of letter knowledge.

4.3.2 Methods

A passive visual-auditory oddball paradigm was conducted to analyze visual-auditory speech discrimination in school children with and without WP (for description, see 3.).

Mixed-model design ANOVAs were performed. To test for a significant vaMMR, we compared the ERPs for standard stimuli with the ERPs for deviant stimuli ($p \leq .05$). Writing abilities (with, without WP) were included as between-subject factor. Analyses were computed on a frontal region of interest (ROI) (F3, FZ, F4), a central ROI (C3, CZ, C4), and a parietal ROI (P3, PZ, P4). Further, because the amount of attention directed towards stimuli could have an effect on potential group differences in visual-auditory speech processing, we compared attention paid towards stimuli between children with and without WP.

4.3.3 Results

Regarding the attention paid towards stimuli, children with and without WP did not differ significantly ($p = .12$). Figure 6 illustrates the vaMMR in response to mouth movements pronouncing syllables out loud. Results showed that children with and without WP do not differ significantly in their vaMMR. The syllables /pa/ and /ga/ are processed differently in both groups. For the syllable /pa/, but not for the syllable /ga/, we found a negativity (200–300 ms after stimulus onset) followed by a second negativity (600–700 ms after stimulus onset). Further, we found a positivity at 800–900 ms after stimulus onset, which was significantly more pronounced for the syllable /ga/ compared to the syllable /pa/.

To evaluate the underlying processes of visual-auditory speech processing in children with and without WP, we conducted temporal principal component analyses (PCA) on the MMR difference wave only at FZ (deviant–standard), as we did not find interactions involving the factors condition and region, but separately for syllables /pa/ and /ga/, as we found interactions involving the factors condition and stimulus-type. Component loadings were used as weights to compute component scores, which were then submitted to a mixed-model design ANOVA in order to analyze whether children with and without WP differ concerning their component scores that were found by PCA.

The PCA revealed four components for both stimuli (see Figure 6), which we interpreted according to their time-point of appearance in relation to the information presented to participants. The first one of these components most likely indicates the processing of the stimulus-onset (Onset). The second component can be viewed as an indicator for visual speech processing (Visual), and the third one as an indicator for auditory speech processing (Auditory) (Chandrasekaran et al., 2009). The fourth component was interpreted as indicating visual-auditory integration (Integration). No differences between the syllables /pa/ and /ga/ were found concerning the components revealed by PCA. However, we found differences between children with and without WP, such that they differed significantly concerning their component scores on the integration component. Children with WP scored negatively, whereas children without WP scored positively.

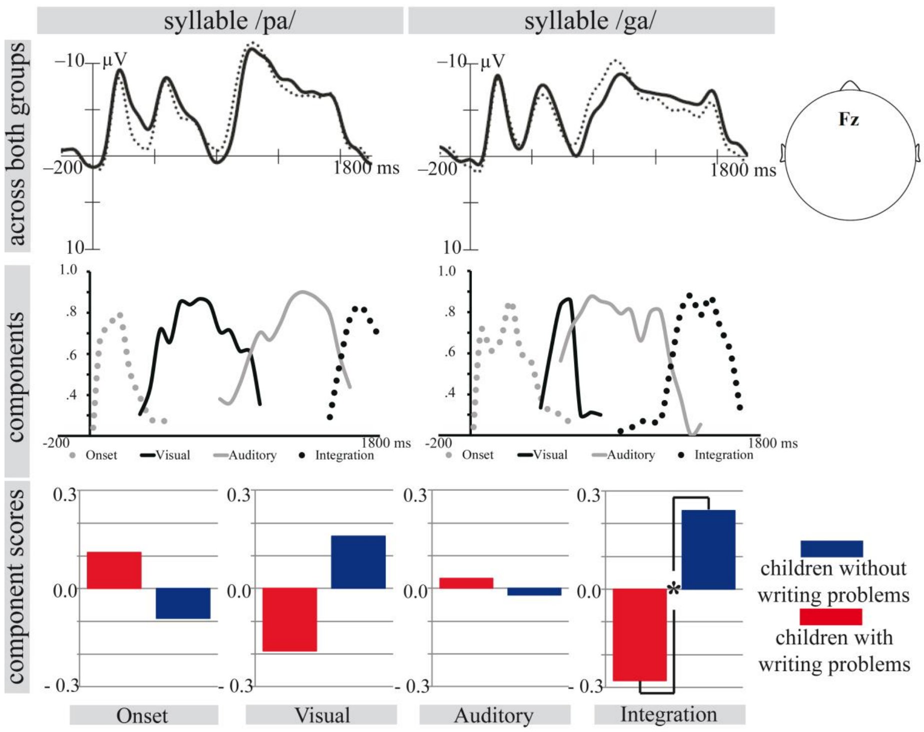

Figure 6. Figure adapted from Schaadt et al. (c, submitted). Top panel illustrates ERPs for standard stimuli (dotted line) and deviant stimuli (solid line) separately for syllables /pa/ and /ga/ across both groups of children. Middle panel shows components for syllables separately. Bottom panel illustrates component scores for children with (red columns) and children without WP (blue columns) collapsed across both syllables as we did not find significant interactions between the factors component scores and syllables. * $p<.05$.

We further controlled for attention paid towards stimuli by adding this variable as a covariate, but no interaction involving attention was significant and we still found significant differences between children with and without WP concerning the integration component.

4.3.4 Discussion

The experiment summarized here investigated whether children with WP exhibit a general verbal integration deficit, independent of letter knowledge, or a specific letter-speech sound integration deficit. Further, we were able to analyze whether visual speech information can be used functionally by school children with WP to successfully compensate for their deficient auditory speech discrimination (Study I). We analyzed the vaMMR in response to mouth movements pronouncing syllables out loud. Generally, we did not find visual-auditory speech discrimination differences between children with and without WP, which would speak in favor of the hypothesis that visual-auditory speech integration is intact in children with WP, when tested independently of letter knowledge (**Hypothesis III.b**). Furthermore, this finding could be attributed to the supportive role of visual speech information during speech processing (Arnold & Hill, 2001; Bernstein et al., 2004), even in children with WP.

However, individuals with DD normally show deficient integration (Blau et al., 2010; Froyen et al., 2011) during the processing of letter-speech sound pairs. We computed PCA and found differences between children with and without WP for the integration component. Children with WP scored negatively and children without WP scored positively on the integration component. The negative score of children with WP on the integration component indicates that the integration component of children with WP contributes less to the overall signal (i.e., vaMMR) compared to the mean of the whole sample. Therefore, it can be concluded that children with WP show reduced integration abilities during the discrimination of visual-auditory speech stimuli compared to children without WP (**Hypothesis III.a**).

5 General Discussion

5.1 Summary of Results

Three studies were conducted to assess the relationship between auditory, visual, and visual-auditory speech processing and writing abilities in German school children using ERP measures.

Study I generally confirms previous findings of auditory speech discrimination deficits in school children with WP. By applying a retrospective analysis of the ERPs registered during infancy, we could further determine the time-point when auditory speech discrimination deficits in German infants with later WP start to develop, which is at the age of 5 months.

Study II tested visual speech discrimination in children with WP, as speech processing is a multisensory phenomenon and visual speech information was generally found to support speech processing. We found distributional differences of the vMMR between children with and without WP. Children without WP show a posterior scalp distribution, whereas children with WP show a more anterior scalp distribution during visual speech discrimination that can normally be observed during auditory speech discrimination. We interpreted these findings as an attempt of children with WP to anticipate the potentially upcoming auditory signal in order to compensate for their auditory speech discrimination deficit (i.e., phonological deficit).

Study III aimed to investigate whether school children with WP exhibit a general verbal integration deficit during visual-auditory speech processing, relatively independent of letter knowledge, or a specific deficit during the integration of letters and speech sounds. We did not find any vaMMR differences during visual-auditory speech discrimination between children with and without WP, maybe suggesting that indeed, visual speech information can support children with WP during speech processing. However, looking more closely at the underlying processes of visual-auditory speech processing by computing a PCA, we found integration deficits of visual and auditory speech information in children with WP. These results suggest deficient letter-speech sound integration to be caused by a general visual-auditory speech integration deficit, and indicate that auditory speech discrimination deficits cannot be entirely compensated by the processing of visual speech information.

In the following, these findings will be discussed in relation to the theories concerning the underlying causes of DD (see Introduction), regarding implications for therapeutic interventions for individuals with DD, and concerning implications for the early risk diagnosis of DD. The results of the three studies will be integrated and I will raise some limitations of the studies presented and provide suggestions on how to overcome these limitations in future research.

5.2 Relation of the Current Findings to Theories Concerning the Underlying Causes of Developmental Dyslexia

5.2.1 Auditory Speech Processing and Developmental Dyslexia Theories

By investigating auditory speech discrimination by means of ERPs in school children with and without WP in response to natural syllables, we found auditory speech processing deficits in children with WP, which is in line with other studies (Baldeweg, Richardson, Watkins, Foale, & Gruzelier, 1999; Kujala et al., 2000; Schulte-Körne et al., 1998). These previous findings and our results speak in favor of the *phonological theory*, postulating DD to be caused by a cognitive deficit specific to representations and processing of speech sounds (Liberman, 1973; Snowling, 1998). Yet, results of Study I do not allow to exclude other theories such as the *auditory processing deficit theory* (Tallal et al., 1993), postulating basic, non-linguistic deficits in temporal resolution of rapidly changing auditory stimuli to cause deficient speech perception as a secondary symptom. In Study I, we did not analyze auditory processing deficits. However, for example, Schulte-Körne et al. (1998) and Paul et al. (2006) found significantly reduced speech discrimination capacities in German school children with DD, but no deficient simple sound discrimination, which would argue against the *auditory processing deficit theory* and in favor of the *phonological theory*.

Beyond auditory speech discrimination deficits in children with WP, we observed qualitative differences, namely different aMMR polarity, in response to the syllable /pa/ and quantitative differences, namely different aMMR amplitude, in response to the syllable /ga/, between children with and without WP. Qualitative differences between aMMR of school children with and without WP could be explained by a developmental delay of school children with WP (see also Urs Maurer, Kerstin Bucher, Silvia Brem, & Daniel Brandeis, 2003), as a positive aMMR is associated with a less mature response depending on the individual development (Mueller, Friederici, & Männel, 2012). The developmental delay and hence, different aMMR polarities might be associated with the involvement of different sources generating the aMMR (U. Maurer, K. Bucher, S. Brem, & D. Brandeis, 2003), which are the STG associated with the bottom-up processing of auditory deviancy, and the inferior frontal gyrus (IFG) associated with top-down processes modulating the deviance detection by attentional switches (Restuccia, Della Marca, Marra, Rubino, & Valeriani, 2005). STG and IFG activity were found to be responsible for a negative aMMR in adults, whereas a positive aMMR in kindergarteners was only found to be associated with STG activity (U. Maurer et al., 2003). Based on these findings, we thus concluded the positive aMMR in our sample of school children with WP to be associated with reduced IFG involvement and thus, top-down attentional switch modulation problems during deviance detection, which, in addition, questions the independency of attention of the aMMR (Näätänen et al., 1993). This interpretation fits the *attentional sluggishness theory*, which postulates auditory deficits to be attention related (Lallier et al., 2009), receiving further support by high comorbidity between DD and attention-deficit-hyperactivity disorder (Germanò, Gagliano, & Curatolo, 2010).

Yet, we also found a positive aMMR in children without WP in response to the syllable /ga/, which was, however, less pronounced than in children with WP. Next to a developmental delay and attention-related deficits, a second factor should, therefore, be discussed in the context of aMMR polarity, namely task difficulty. Wetzel, Berti, Widmann, and Schröger (2004) found a positive aMMR also to be elicited in normally developing children during difficult discrimination tasks, influenced by the length of the ISI (Schröger & Winkler, 1995) and stimulus complexity (Ruhnau, Wetzel, Widmann, & Schröger, 2010). In Study I, a long ISI (1450–1750 ms) and complex natural syllables were used. Importantly, the discrimination of syllables beginning with /g/ is more difficult than the discrimination of syllables beginning with /p/ (Masterson, Hazan, & Wijayatilake, 1995). As /pa/ is a more dominant plosive sound, top-down attentional switch modulation during deviance detection of the syllable /ga/ out of a stream of the syllable /pa/ could be reduced, leading to a positive aMMR, even in school children without WP. Therefore, results of Study I should only carefully be interpreted in line with the *attentional sluggishness theory*, as children without WP also seem to have attentional switch modulation problems during deviance detection in difficult discrimination tasks.

As DD appears to be such a diverse disorder, there is probably an interplay of many causes leading to the development of DD and there are first attempts to address this issue by suggesting DD subtypes (e.g., Heim et al., 2008), which are discussed in more detail in section 5.5.

5.2.2 Visual Speech Processing and Developmental Dyslexia Theories

The *magnocellular visual deficit theory* (Stein, 2001) suggests deficient coherent visual motion detection and reduced visual speed discrimination to cause DD, depending on neurodevelopmental abnormalities of the magnocellular system (Meng et al., 2011; Talcott et al., 2003). As visual motion detection is important for perceiving the word-form and letter positions in words (Demb et al., 1998), but also for perceiving visual speech information (for review, see Campell, 2008), one could hypothesize deficient visual speech discrimination in children with WP. Yet, in Study II we did not find deficient visual speech processing in children with WP, but differences in the way of processing of visual speech information between children with and without WP. Thus, results can generally not be interpreted as a visual processing deficit. It is more likely that children with WP try to use visual speech information in order to compensate for their phonological deficit. However, the *magnocellular visual deficit theory* was not formulated to explain deficient visual speech processing, but general visual processing deficits. Thus, we cannot expulse the *magnocellular visual deficit theory*, but conclude that it cannot explain distributional differences between children with and without WP.

5.2.3 Visual-Auditory Speech Processing and Developmental Dyslexia Theories

One theory concerning visual-auditory integration of letter and speech sounds during reading is the DRC-model (Coltheart et al., 2001). Three different routes are suggested describing pathways between perceiving printed information and reading out loud (see also section 1.2.3). For all three routes, the acquisition and execution of grapheme-phoneme correspondence rules are required. Individuals with DD show deficiencies during the acquisition and utilization of letter-speech sound correspondences (Froyen et al., 2009; Froyen et al., 2011). However, as outlined in the introduction, studies concerning the integration of letter-speech sounds cannot differentiate between specific integration deficits of letter-speech sound pairs and a general verbal integration deficit independent of letter knowledge. In Study III, we analyzed visual-auditory speech discrimination relatively independent of letter knowledge. In order to successfully discriminate bimodally presented stimuli, namely visual and auditory speech information, they need to be integrated. By analyzing the vaMMR amplitude, we found that children with WP do not seem to exhibit a general verbal integration deficit. We did not find any vaMMR amplitude differences between children with and without

WP and it could be concluded that deficient integration of letter-speech sound pairs (Froyen et al., 2009; Froyen et al., 2011) can be attributed to a consequence of unsuccessful literacy acquisition rather than to causing DD. However, it should be considered that underlying components of the vaMMR in response to the syllables overlap, which could also explain why we did not find any vaMMR amplitude differences.

Looking more closely at the underlying processes during visual-auditory speech processing, a PCA revealed deficient integration of visual and auditory speech information in children with WP. We found that children with WP scored negatively on the fourth component, which we interpreted as indicating integration processes, whereas children without WP scored positively. These findings point to integration difficulties in children with WP and would speak in favor of general verbal integration deficits in individuals with DD, independent of letter knowledge, which would then cause deficient letter-speech sound integration. Further research needs to confirm our results in order to reformulate theories on grapheme-phoneme correspondences into theories focusing on more general verbal integration deficits, which would consequently lead to difficulties in learning letter-speech sound correspondences.

5.3 Visual and Visual-Auditory Speech Processing in Children with Writing Problems–a Denied Research Field

In Study II and Study III, we analyzed visual and visual-auditory speech processing in children with WP. As far as we are concerned, these are the first studies investigating speech processing beyond the auditory modality in relation to reading and writing impairments in the ERP. As visual speech information, however, supports or can even replace the processing of auditory speech information (Arnold & Hill, 2001; Bernstein et al., 2004), this research promises more insight into speech processing “deficits” of individuals with DD.

The use of the supportive function of visual speech information develops early in life. Already twelve-month-old infants concentrate on visual speech information, namely mouth movements, during difficult auditory communication conditions (i.e., non-native monologue) in order to support speech processing (Lewkowicz & Hansen-Tift, 2012). This strategy might continue into adolescence or even adulthood in individuals with WP in order to compensate for their phonological deficit (Pekkola et al., 2006). Accordingly, the anterior vMMR, which we found in Study II during visual speech processing in children with WP, might be regarded as an anticipation of the potentially upcoming auditory signal, in an attempt to compensate for their phonological deficit (Snowling, 1998). This interpretation finds support, firstly by our finding that low phonological awareness abilities in children with WP go along with a more pronounced anterior vMMR, and secondly by Pugh et al. (2001), who suggested three circuits to be involved in the processing of written language:

1) The ventral circuit (including lateral extrastriate areas and a left inferior occipito-temporal area) is involved in the identification of linguistically structured memory based words, and children with DD show reduced activity compared to their normally developing peers (Salmelin, Service, Kiesilä, Uutela, & Salonen, 1996).

2) The dorsal circuit (including angular gyrus, supramarginal gyrus, Wernicke's area) is involved in the integration of orthographic, phonological, and lexical-semantic dimensions, and was also found to show less activity in individuals with DD compared to their normally developing peers (Brambati et al., 2006).

3) The anterior circuit (including Broca's area in the IFG) is involved in fine-grained articulatory recoding. Here, individuals with DD show enhanced activity compared to their normally developing peers during the processing of visually presented words (Kronbichler et al., 2006). This enhanced activation was interpreted as a compensatory process in light of an impaired development of the posterior part of the network and the phonological deficit in individuals with DD (see also Shaywitz & Shaywitz, 2008).

Importantly, in Study I, we found a more pronounced aMMR in children with WP in response to deviant syllables, which we interpreted to be associated with reduced IFG involvement and thus, top-down attentional switch modulation problems during deviance detection, due to their phonological deficit. Thus, the anteriorly distributed vMMR in children with WP might indicate an attempt to enhance IFG activity to anticipate the potentially upcoming auditory signal and to support top-down attentional switch modulation during deviance detection. Additionally, the distribution of the vMMR and aMMR was compared to further support the claim of the anterior vMMR in children with WP to mirror an attempt to compensate for their phonological deficit. The ANOVA was extended by a further factor (i.e., experiment; visual, auditory). Results revealed a significant interaction between experiment, region, and writing abilities ($p<.01$), though only for children without WP, such that there was a significant anterior aMMR and a significant posterior vMMR. Children with WP did not show any distributional differences between auditory and visual speech processing, suggesting that both kinds of stimuli were processed similarly.

In Study III we could analyze whether this possible compensatory process is functional, expressly whether visual speech information supports auditory speech processing in individuals with DD. Indeed, we did not find significant vaMMR differences between children with and without WP. Although PCA revealed differences between children with and without WP during the integration of visual and auditory speech information, we would still view the data to speak in favor of the supportive function of visual speech information for individuals with DD. A post-hoc linear regression analysis showed that the integration abilities of children with WP are negatively affected by the aMMR ($\beta = -.37$; $p=.09$) and positively affected by the vMMR ($\beta = .51$; $p=.03$) ($R^2 = .26$; $p<.08$). These results show that enhanced auditory speech processing capacities (i.e., negative aMMR) and a stronger attempt to compensate for phonological deficits (i.e., a more positive anterior vMMR) are associated with enhanced integration abilities. However, to track down the interaction between auditory speech processing, visual speech processing, and integration abilities more thoroughly, a further predictor variable was added: the interaction between the vMMR and the aMMR. We still found a more negative aMMR to be associated with better integration abilities ($\beta = -.76$; p=.07), but the vMMR was no longer associated with integration abilities ($\beta = -.01$; p=.80). When looking at the interaction between aMMR and vMMR, we found a positive impact on integration abilities ($\beta = .95$; p=.10) ($R^2 = .32$; $p<.09$). This might indicate that children with reduced auditory speech processing capacities are still able to integrate visual and auditory speech information when the suggested visual compensatory process is more pronounced. These results can, however, only be reported for the syllable /pa/ and not for the syllable /ga/, which can be explained by the fact that visual speech information of the syllable /pa/ is more differentiating and informative compared to the syllable /ga/, and so can be used for compensation more easily.

It has to be noted that our interpretation is not in accordance with findings by de Gelder and Vroomen (1998), who found reduced abilities in identifying the syllables /ba/ and /da/ that were either presented visually alone or auditorily alone in children with DD compared to children without DD. However, when children with DD had to identify the syllable /ba/ and /da/ when they were presented visually and auditorily together, they did perform similarly to children without DD (de Gelder & Vroomen, 1998). This again points towards the supportive function of visual speech information during speech processing in children with DD.

Taken together, we found children with WP to exhibit auditory speech processing deficits (i.e., phonological) and integration deficits of visual and auditory speech information. Further, we found that visual speech information might support children with WP during speech processing and the integration of visual and auditory speech information. These findings give implications for therapeutic interventions for individuals with DD, which I will outline in the following section.

5.4 Implications for Developmental Dyslexia Therapies

Therapeutic interventions for individuals with DD can be differentiated into symptomatic and causal therapeutic interventions. Symptomatic interventions employ systematic methods based on learning theory, where reading and writing or precursors of these abilities are trained directly. Causal interventions try to eliminate postulated causes underlying the learning disabilities, with treatment measures that focus on training low-level functions (von Suchodoletz, 2010). One measure for training prerequisites for literacy acquisition is called "hearing, listening, learning" (Küspert & Schneider, 2008). This training-program is based on the assumption of phonological deficits (Snowling, 1998) in individuals with later DD and tries to compensate for these deficits by practicing, for example, rhyming and syllable clapping to enhance phonological awareness. Training phonological awareness abilities seems highly recommended considering our results of deficient auditory speech processing in children with WP. Indeed, phonological awareness training in children with learning problems leads to enhanced and more resistant cortical responses to syllables (i.e., /ga/, /da), which, importantly, is accompanied by improvement in behavioral performance (Hayes, Warrier, Nicol, Zecker, & Kraus, 2003).

Another training measure, which seems to support individuals with DD, is a causal intervention by Dreher (2006), where children are asked to perform large mouth movements to memorize the picture of the mouth during certain speech sounds. Dreher (2006) explains the success of the training by referring to deficient mouth movement coordination in children with DD. However, referring to our findings of Study II and Study III, one could associate the success of this training with the supportive function of visual speech information for speech processing, which might be further supported by training large mouth movements.

Some intervention studies also showed audiovisual training programs to improve reading and writing abilities in individuals with DD. Lovio, Halttunen, Lyytinen, Näätänen, and Kujala (2012) trained 6-year-old preschoolers with difficulties in reading related skills, either with an intervention game where letter-sound associations are trained, or with mathematical exercise. Only children that were trained in letter-sound association progressed in reading related skills. However, as discussed above, we suggest a general verbal integration deficit, which should be trained in individuals with DD. Interestingly, it was demonstrated that normally reading and writing adults benefit from verbal audiovisual training, in that auditory perceptual learning for speech perception is enhanced (Bernstein, Auer, Eberhardt, & Jiang, 2013). Considering these findings and our results, we recommend visual speech processing and visual-auditory speech integration training, next to phonological training, for individuals with DD and at risk of developing DD.

For the realization of therapeutic interventions early diagnosis is required. Currently, the earliest psychometric test for diagnosing the risk of developing DD is the BISC (Jansen et al., 2002), which can be applied 10 months before school enrollment. In order to train important prerequisites for literacy acquisition in children at risk of DD, 10 months is a short period of time and therapeutic interventions are more promising when applied, at least 2 years before school enrollment. For this to occur, diagnostic tools are required which are currently unavailable. In the following section, I will discuss findings of the current research project in terms of implications for the early diagnosis of the risk of developing DD.

5.5 Auditory Speech Processing and Implications for the Early Diagnosis of the Risk of Developmental Dyslexia

As mentioned before, certain characteristics (e.g., objectivity, independency of attention) of the aMMR led researchers to hope that it might be used as a diagnostic tool for identifying the risk for DD (Bishop, 2007). Moreover, the aMMR can be registered relatively reliably at the individual level. Bishop and Hardiman (2010) identified an individual aMMR in 82% of adult participants in response to pure tones. These features make the aMMR very attractive as a potential diagnostic tool for deficient auditory speech discrimination as an early indicator for children's problems in later language and literacy acquisition. In our retrospective analyses, we found differences in the aMMR in response to natural syllables between infants with and without later diagnosed WP at the age of 5 months, but not at the age of 1 month. Hence, 5-month-old infants without later WP are able to discriminate natural syllables, but 5-month-old infants with later WP are not (see also Leppänen et al., 2002; Pihko et al., 1999). However, the effect size indicating the variance explained by the differences between infants with and without later WP at the age of 5 months is small ($\eta_p^2 = .08$) and exploratory regression analysis did not show the infant aMMR to be predictive for later writing abilities ($\beta = -.02$). It can therefore be concluded that the aMMR is not suitable, at least at this young age, to reliably diagnose the risk for later DD, and it is questionable whether the aMMR can be used for diagnostic measures later in development, because ERPs are prone to noise.

Another, maybe more promising approach and less prone to noise, is the utilization of brainstem potentials to diagnose the early risk for DD. Banai et al. (2009), demonstrated a relationship between timing of subcortical auditory processing, namely brainstem potentials of speech and reading abilities. Specifically, subcortical speech encoding reflecting the utilization of stimulus regularities, differentiation of stop consonants, and robustness of neural synchrony, were found to predict 73% of the variance in reading scores (Hornickel, Chandrasekaran, Zecker, & Kraus, 2011) of school children between the ages of 8 and 13 years. Despite the high-explained variance of reading scores, further research needs to analyze whether the found relationship can be explained by deficits leading to DD, and thus, underpinning the suitability of brainstem potentials for diagnostic measures, or whether reported deficits are caused by unsuccessful literacy acquisition itself. This can be realized in a longitudinal design, investigating children at risk of developing DD before school enrollment, and reading and writing abilities after around 2 years of literacy instruction.

5.6 Limitations of the Current Research Project and Suggestions for Further Research

Concerning Study I, in which we analyzed auditory speech discrimination, one major critique is that stimuli at infant age and school age cannot be compared directly. This becomes apparent by the negative aMMR in response to /ga/, which we found in 5-month-old infants without later WP, but the positive aMMR in response to /ga/ in these very same children at school age. We explained these differences by the fact that infants were tested with a natural syllable, which was shorter in length (150 ms) and therefore less complex, compared to the stimulus used at school age (409 ms). Additionally, the ISI for the infants' testing was shorter (750 ms vs. 1450–1750 ms), supporting a less complicated detection of deviance (Schröger & Winkler, 1995). Stimulus complexity and length of ISI influence task difficulty, which can lead to the elicitation of a positive aMMR, even in older children that normally can already generate a negative aMMR (Wetzel et al., 2004). Different stimuli can be justified by the retrospective character of the study. We could also have used /ga/ and /da/ as stimuli at school age. But, /da/ and /ga/ cannot be easily differentiated visually und therefore we decided for comparability of the three experiments concerning auditory, visual, and visual-auditory speech discrimination at school age.

In addition, there is a second critique concerning the utilization of the syllables /pa/ and /ga/. Phonemes can be characterized by the site of articulation, namely labial, alveolar, and velar, and kind of articulation, namely plosive, fricative, and nasal. Further, they are characterized in terms of a voiced or unvoiced articulation. In DD research, normally /ga/ and /da/ are used, because they are both plosive and voiced and so just differ in terms of their site of articulation (/da/ is alveolar and /ga/ is velar). /Pa/ and /ga/ are also both plosive sounds, but /pa/ is unvoiced and /ga/ is voiced and the site of articulation varies, with /pa/ being labial and /ga/ being velar. As described above, we decided to use /pa/ and /ga/, because they can be discriminated not only auditorily but also visually.

Future investigations should use different syllables to confirm our results not only concerning auditory speech discrimination, but also visual and visual-auditory speech discrimination. One possibility could be to use /ba/ and /ga/, as they can be discriminated both auditorily and visually and, as they are both voiced, they differ less than /pa/ and /ga/. Furthermore, a larger variety of syllable pairs should be analyzed in the future to gain a better understanding of the underlying speech discrimination deficit in individuals with DD. So far, most researchers only used the syllables /da/, /ga/, and /ba/ (for an overview, see Bishop, 2007).

Further, we did not analyze low-level auditory processing in our sample and were therefore not able to reject deficient low-level auditory processing as an explanation for auditory speech processing deficits, which we found in Study I. Low-level auditory processing could have been investigated by analyzing the aMMR in response to simple sounds with a short ISI. However, Schulte-Körne et al. (1998, 2001) and Paul et al. (2006) did not find auditory processing differences between German individuals with and without DD in response to simple sounds, and recent studies found a relationship between reading and subcortical auditory processing of speech, but not between reading and pitch encoding (Banai et al., 2009).

As discussed above, our studies were not suitable to accept or expulse one of the theories concerning the underlying causes of DD (see section 5.2). This difficulty might also be attributed to the diversity of DD. First attempts to address this issue suggest DD subtypes. For example, Heim et al. (2008) postulated one group of individuals with DD with phonological deficits, one group with low-level auditory deficits, and one group with magnocellular deficits (see also Schulte-Körne & Bruder, 2010). It would have been interesting to analyze auditory, visual, and visual-auditory speech discrimination in relation to these three different subtypes. However, sample size was not sufficient for high enough statistical power, which should, however, be realized in future research. Concerning auditory speech processing, I would expect the subtype with phonological deficits to be more impaired than the other two subtypes. Results concerning visual speech processing in this research project were interpreted in terms of a compensation for a phonological deficit. However, it is possible that individuals with a specific magnocellular deficit would show reduced posterior vMMR amplitude, compared to individuals with a phonological deficit, who might show a more anterior vMMR during visual speech discrimination, compared to normally developing controls. According to these hypotheses, it could be concluded that in the current research project, participating school children belonged to the phonological subtype. We observed deficient auditory speech processing and possible compensation for this phonological deficit by relying on visual speech information. Phonological deficits are the most frequently reported cases in the DD population (Mann & Liberman, 1984; Moll et al., 2014; Snowling, 1998) and therefore a larger sample probably would have been necessary for also acquiring the less common magnocellular subtype (Schulte-Körne & Bruder, 2010).

During visual and visual-auditory speech processing, attention paid towards stimuli is important for gaining a reliable MMR. For controlling attention, we analyzed differences in eye-movements (i.e., horizontal EOG, vertical EOG) and attention paid towards stimuli (i.e., rated by an independent observer) between children with and without WP. However, measurement of eye-movements by using EOG channels is not completely reliable and the rated attention after the experimental block is dependent on the subjectivity of the observer. A possibility for controlling for eye-movements is to use an eye-tracker and reject trials when participants do not focus the area of interest, namely the mouth. However, eye-tracking is difficult in young children. A further possibility would be to send a trigger by an independent observer every time the child is not focusing on the stimulus, and reject trials indicated as not being attended to.

Concerning letter-speech sound integration deficits in individuals with DD, I argued that findings could be a secondary effect, such that these deficits are evoked by unsuccessful literacy acquisition. To this end, we also cannot exclude that visual speech discrimination differences between children with and without WP, and visual-auditory speech integration deficits in children with WP, are also caused by unsuccessful literacy acquisition. Future research needs to analyze, especially, visual and visual-auditory speech discrimination in preschoolers at risk of developing DD. Here, similar findings like the found differences between children with and without WP would emphasize training of visual speech processing and visual and auditory speech integration, next to phonological training in preschoolers at risk of developing DD. The current research project mainly focused on visual and auditory processing and their integration. Thus, we cannot expulse the possibility of a more general deficit of, for example, the suggested magnocellular system (Stein, 2001). Few studies have reported reduced tactile processing in individuals with DD (Grant, Zangaladze, Thiagarajah, & Sathian, 1999) and reduced temporal processing abilities of bimodally presented visuotactile stimuli (Virsu, Lahti-Nuuttila, & Laasonen, 2003). Future DD research should further investigate processing abilities in different modalities and their integration to differentiate between a more general deficit and a deficit specific to visual and auditory information.

5.7 Conclusions

In conclusion, we found auditory speech discrimination deficits in response to natural stimuli in German school children with WP, confirming a close relationship between children's phonological and literacy skills. In contrast to other studies analyzing infants at risk of developing DD, we could show in a retrospective analysis that auditory speech discrimination deficits in infants with later diagnosed WP already start to develop at the age of 5 months. However, as the aMMR is probably too prone to noise, at least at this young age, further research is needed to evaluate the suitability of other psychophysiological measures, such as brain stem potentials, for the early diagnosis of the risk of developing DD in the individual child. Further, to our knowledge, we conducted the first study analyzing visual speech processing by measuring ERPs in children with WP. Interestingly, results indicate that visual speech information might even support children with WP during speech processing. In a further study, we analyzed visual-auditory speech integration and found deficits in children with WP. However, importantly, additional analyses showed that children with reduced auditory speech processing capacities but enhanced visual compensation strategies showed better performance in visual-auditory speech integration. Thus, results speak for general deficient verbal integration independent of letter knowledge in children with WP, which is modulated by auditory and visual speech processing and their interaction. The combined results of all three studies suggest that speech processing should not be interpreted as a monosensory phenomenon, but rather as a multisensory phenomenon, especially when investigating the underlying causes of language deficits, such as reading and writing problems. Future research needs to analyze the interplay between visual, auditory, and visual-auditory speech processing in more detail under consideration of DD subtypes to form a profound principle for the conceptualization of successful training programs.

References

AmericanPsychiatricAssociation. (2013). *Diagnostic and Statistical Manual of Mental Disorders: Dsm-5*: Amer Psychiatric Pub Incorporated.

Arnal, L. H., Morillon, B., Kell, C. A., & Giraud, A. L. (2009). Dual neural routing of visual facilitation in speech processing. *The Journal of neuroscience, 29*(43), 13445-13453. doi:10.1523/JNEUROSCI.3194-09.2009

Arnold, P., & Hill, F. (2001). Bisensory augmentation: A speechreading advantage when speech is clearly audible and intact. *British Journal of Psychology, 92*(2), 339-355. doi:10.1348/000712601162220

Baddeley, A. (2003). Working memory and language: an overview. *Journal of Communication Disorders, 36*(3), 189-208. doi:10.1016/s0021-9924(03)00019-4

Baddeley, A., & Wilson, B. A. (1993). A developmental deficit in short-term phonological memory: implications for language and reading. *Memory, 1*(1), 65-78. doi:10.1080/09658219308258225

Baldeweg, T., Richardson, A., Watkins, S., Foale, C., & Gruzelier, J. (1999). Impaired Auditory Frequency Discrimination in Dyslexia Detected with Mismatch Evoked Potentials. *Annals of Neurology, 45*, 495-503.

Banai, K., Hornickel, J., Skoe, E., Nicol, T., Zecker, S., & Kraus, N. (2009). Reading and subcortical auditory function. *Cereb Cortex, 19*(11), 2699-2707. doi:10.1093/cercor/bhp024

Benoît, C., Guiard-Marigny, T., Goff, B., & Adjoudani, A. (1996). Which components of the face do humans and machines best speechread? In D. Stork & M. Hennecke (Eds.), *Speechreading by Humans and Machines* (Vol. 150, pp. 315-328): Springer Berlin Heidelberg.

Bernstein, L. E., Auer, E. T., Jr., Eberhardt, S. P., & Jiang, J. (2013). Auditory Perceptual Learning for Speech Perception Can be Enhanced by Audiovisual Training. *Front Neurosci, 7*, 34. doi:10.3389/fnins.2013.00034

Bernstein, L. E., Auer, E. T., Jr., & Takayanagi, S. (2004). Auditory speech detection in noise enhanced by lipreading. *Speech Communication, 44*(1-4), 5-18. doi:10.1016/j.specom.2004.10.011

Birbaumer, N., & Schmidt, R. F. (2006). Methoden der Biologischen Psychologie *Biologische Psychologie* (& ed.). Heidelberg: Springer.

Birch, H. G., & Belmont, L. (1964). Auditory Visual Integration in Normal and Retarded Readers*. *American Journal of Orthopsychiatry, 34*, 48-96.

Bishop, D. V. (2007). Using mismatch negativity to study central auditory processing in developmental language and literacy impairments: where are we, and where should we be going? *Psychol Bull, 133*(4), 651-672. doi:10.1037/0033-2909.133.4.651

Bishop, D. V., & Hardiman, M. J. (2010). Measurement of mismatch negativity in individuals: a study using single-trial analysis. *Psychophysiology, 47*(4), 697-705. doi:10.1111/j.1469-8986.2009.00970.x

Blau, V., Reithler, J., van Atteveldt, N., Seitz, J., Gerretsen, P., Goebel, R., & Blomert, L. (2010). Deviant processing of letters and speech sounds as proximate cause of reading failure: a functional magnetic resonance imaging study of dyslexic children. *Brain, 133*(Pt 3), 868-879. doi:10.1093/brain/awp308

Blau, V., van Atteveldt, N., Ekkebus, M., Goebel, R., & Blomert, L. (2009). Reduced neural integration of letters and speech sounds links phonological and reading deficits in adult dyslexia. *Curr Biol, 19*(6), 503-508. doi:10.1016/j.cub.2009.01.065

Brambati, S. M., Termine, C., Ruffino, M., Danna, M., Lanzi, G., Stella, G., . . . Perani, D. (2006). Neuropsychological deficits and neural dysfunction in familial dyslexia. *Brain Res, 1113*(1), 174-185. doi:10.1016/j.brainres.2006.06.099

Campbell, R. (2008). The processing of audio-visual speech: empirical and neural bases. *Philosophical transactions of the Royal Society B, 363*(1493), 1001-1010. doi:10.1098/rstb.2007.2155

Carrion-Castillo, A., Franke, B., & Fisher, S. E. (2013). Molecular genetics of dyslexia: an overview. *Dyslexia, 19*(4), 214-240. doi:10.1002/dys.1464

Chandrasekaran, C., Trubanova, A., Stillittano, S., Caplier, A., & Ghazanfar, A. A. (2009). The natural statistics of audiovisual speech. *PLoS Comput Biol, 5*(7), e1000436. doi:10.1371/journal.pcbi.1000436

Cheour, M., Ceponiene, R., Lehtokoski, A., Luuk, A., Allik, J., Alho, K., & Näätänen, R. (1998). Development of language-specific phoneme representations in the infant brain. *nature neuroscience, 1*(5), 351-353.

Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). DRC: A Dual Route Cascaded Model of Visual Word Recognition and Reading Aloud. *Psychological Review, 108*(1), 204-256. doi:10.1037/0033-295X.108.1.204

Corbera, S., Escera, C., & Artigas, J. (2006). Impaired duration mismatch negativity in developmental dyslexia. *NeuroReport, 17*, 1051-1055.

Czamara, D., Bruder, J., Becker, J., Bartling, J., Hoffmann, P., Ludwig, K. U., . . . Schulte-Körne, G. (2011). Association of a rare variant with mismatch negativity in a region between KIAA0319 and DCDC2 in dyslexia. *Behav Genet, 41*(1), 110-119. doi:10.1007/s10519-010-9413-6

Czigler, I., Weisz, J., & Winkler, I. (2006). ERPs and deviance detection: visual mismatch negativity to repeated visual stimuli. *Neurosci Lett, 401*(1-2), 178-182. doi:10.1016/j.neulet.2006.03.018

de Gelder, B., & Vroomen, J. (1998). Impaired Speech Perception in Poor Readers: Evidence from Hearing and Speech Reading. *Brain and Language, 64*, 296-281.

Demb, J. B., Boynton, G. M., Best, M., & Heeger, D. J. (1998). Psychophysical evidence for a magnocellular parthway deficit in dyslexia. *Vision Research, 38*, 1555-1559. doi:10.1016/S0042-6989(98)00075-3

Dreher, H. (2006). *Kybernetische Methode - eine sinnvolle Erweiterung logopädischer Behandlung mit Blick auf das schulische Anforderungsprofil*. Paper presented at the Schweizer Arbeitsgemeinschaft für Logopädie Tagung (SAL-Tagung), Zurich.

Edgar, J., Stewart, J., & Miller, G. A. (2005). Digital filters in ERP research. In C. Handy (Ed.), *Event-related potentials: A handbook* (pp. 85-113). Cambridge: MIT Press.

Ehri, L. C. (2005). Learning to Read Words: Theory, Findings, and Issues. *Scientific Studies of Reading, 9*(2), 167-188. doi:10.1207/s1532799xssr0902_4

Esser, G., Wyschkon, A., & Schmidt, M. H. (2002). Was wird aus Achtjährigen mit einer Lese- und Rechtschreibstörung. Ergebnisse im Alter von 25 Jahren. *Zeitschrift für Klinische Psychologie und Psychotherapie, 31*(4), 235-242. doi:10.026//1616-3443.31.4.235

Files, B. T., Auer, E. T., Jr., & Bernstein, L. E. (2013). The visual mismatch negativity elicited with visual speech stimuli. *Front Hum Neurosci, 7*, 371. doi:10.3389/fnhum.2013.00371

Friederici, A. D., Friedrich, M., & Christophe, A. (2007). Brain responses in 4-month-old infants are already language specific. *Current Biology, 17*(14), 1208-1211. doi:10.1016/j.cub.2007.06.011

Friederici, A. D., Friedrich, M., & Weber, C. (2002). Neural manifestation of cognitive and precognitive mismatch detection in early infancy. *NeuroReport, 13*(10), 1251-1254.

Froyen, D., Bonte, M., Van Atteveldt, N., & Blomert, L. (2009). The Long Road to Automation: Neurocognitive Development of Letter-Speech Sound Processing. *Journal of Cognitive Neuroscience, 21*(3), 567-580. doi:10.1162/jocn.2009.21061

Froyen, D., Van Atteveldt, N., Bonte, M., & Blomert, L. (2008). Cross-modal enhancement of the MMN to speech-sounds indicates early and automatic integration of letters and speech-sounds. *Neurosci Lett, 430*(1), 23-28. doi:10.1016/j.neulet.2007.10.014

Froyen, D., Willems, G., & Blomert, L. (2011). Evidence for a specific cross-modal association deficit in dyslexia: an electrophysiological study of letter-speech sound processing. *Dev Sci, 14*(4), 635-648. doi:10.1111/j.1467-

7687.2010.01007.x

Germanò, E., Gagliano, A., & Curatolo, P. (2010). Comorbidity of ADHD and Dyslexia. *Dev Neuropsychol, 35*(5), 475-493. doi:10.1080/87565641.2010.494748

Grant, A. C., Zangaladze, A., Thiagarajah, M. C., & Sathian, K. (1999). Tactile perception in developmental dyslexia: a psychophysical study using gratings. *Neuropsychologia, 37*, 1201-1211. doi:10.1016/S0028-3932(99)00013-5

Hari, R., & Renvall, H. (2001). Impaired processing of rapid stimulus sequences in dyslexia. *Trends in Cognitive Science, 5*(12), 525-532. doi:10.1016/S1364-6613(00)01801-5

Hayes, E. A., Warrier, C. M., Nicol, T. G., Zecker, S. G., & Kraus, N. (2003). Neural plasticity following auditory training in children with learning problems. *Clinical Neurophysiology, 114*(4), 673-684. doi:10.1016/s1388-2457(02)00414-5

Heim, S., Grande, M., Pape-Neumann, J., van Ermingen, M., Meffert, E., Grabowska, A., . . . Amunts, K. (2010). Interaction of phonological awareness and 'magnocellular' processing during normal and dyslexic reading: behavioural and fMRI investigations. *Dyslexia, 16*(3), 258-282. doi:10.1002/dys.409

Heim, S., Tschierse, J., Amunts, K., Wilms, M., Vossel, S., Willems, K., . . . Huber, W. (2008). Cognitive subtypes of dyslexia. *Acta neurobiologiae experimentalis, 68*, 73-82.

Hockfield, S., & Sur, M. (1990). Monoclonal Antibody Cat-301 Identifies Y-Cells in the Dorsal Lateral Geniculate Nucleus of the Cat. *The Journal of Comparative Neurology, 300*, 320-330.

Hornickel, J., Chandrasekaran, B., Zecker, S., & Kraus, N. (2011). Auditory brainstem measures predict reading and speech-in-noise perception in school-aged children. *Behav Brain Res, 216*(2), 597-605. doi:10.1016/j.bbr.2010.08.051

Jansen, H., Mannhaupt, G., Marx, H., & Skowronek, H. (2002). *Bielefelder*

Screening zur Früherkennung von Lese-Rechtschreibschwierigkeiten (BISC). Göttingen: Hogrefe.

Jansen, H., & Marx, H. (1999). *Phonologische Bewusstheit und ihre Bedeutung für den Schriftspracherwerb* (Vol. 2): Forum Logopädie.

Kronbichler, M., Hutzler, F., Staffen, W., Mair, A., Ladurner, G., & Wimmer, H. (2006). Evidence for a dysfunction of left posterior reading areas in German dyslexic readers. *Neuropsychologia, 44*(10), 1822-1832. doi:10.1016/j.neuropsychologia.2006.03.010

Kujala, T., Lovio, R., Lepistö, T., Laasonen, M., & Näätänen, R. (2006). Evaluation of multi-attribute auditory discrimination in dyslexia with the mismatch negativity. *Clinical Neurophysiology, 117*(4), 885-893. doi:10.1016/j.clinph.2006.01.002

Kujala, T., Myllyviita, K., Tervaniemi, M., Alho, K., Kallio, J., & Näätänen, R. (2000). Basic auditory dysfunction in dyslexia as demonstrated by brain activity measurements. *Psychophysiology, 37*(2), 262-266. doi:10.1111/1469-8986.3720262

Küspert, P., & Schneider, W. (2008). *Hören, Lauschen, Lernen. Sprachspiele für Kinder im Vorschulalter.Würzburger Trainingsprogramm zur Vorbereitung auf den Erwerb der Schriftsprache*. Göttingen: Vandenhoeck & Ruprecht GmbH & Co. KG.

Kutas, M., van Petten, C., & Kluender, R. (2005). Psycholinguistic electrified II: 1994-2005. In M. J. Traxler & M. A. Gernsbacher (Eds.), *Handbook of psycholinguistics* (pp. 659-724). San Diego: Academic Press.

Lallier, M., Thierry, G., Tainturier, M. J., Donnadieu, S., Peyrin, C., Billard, C., & Valdois, S. (2009). Auditory and visual stream segregation in children and adults: an assessment of the amodality assumption of the 'sluggish attentional shifting' theory of dyslexia. *Brain Res, 1302*, 132-147. doi:10.1016/j.brainres.2009.07.037

Landerl, K., & Wimmer, H. (2008). Development of word reading fluency and spelling in a consistent orthography: An 8-year follow-up. *Journal of*

Educational Psychology, 100(1), 150-161. doi:10.1037/0022-0663.100.1.150

Lenhard, W., & Schneider, W. (2006). *ELFE 1-6. Ein Leseverständnistest für Erst- bis Sechstklässler*. Göttingen: Hogrefe.

Leppänen, P. H., Richardson, U., Pihko, E., Eklund, K. M., Guttorm, T. K., Aro, M., & Lyytinen, H. (2002). Brain responses to changes in speech sound durations differ between infants with and without familial risk for dyslexia. *Dev Neuropsychol, 22*(1), 407-422. doi:10.1207/S15326942dn2201_4

Lewkowicz, D. J., & Hansen-Tift, A. M. (2012). Infants deploy selective attention to the mouth of a talking face when learning speech. *Proc Natl Acad Sci U S A, 109*(5), 1431-1436. doi:10.1073/pnas.1114783109

Liberman, I. Y. (1973). Segmentation of the Spoken Word and Reading Acquisition. *Bulletin of the Orton Society, 23*(1), 64-77. doi:10.1007/BF02653842

Lovio, R., Halttunen, A., Lyytinen, H., Näätänen, R., & Kujala, T. (2012). Reading skill and neural processing accuracy improvement after a 3-hour intervention in preschoolers with difficulties in reading-related skills. *Brain Res, 1448*, 42-55. doi:10.1016/j.brainres.2012.01.071

Lovio, R., Näätänen, R., & Kujala, T. (2010). Abnormal pattern of cortical speech feature discrimination in 6-year-old children at risk for dyslexia. *Brain Res, 1335*, 53-62. doi:10.1016/j.brainres.2010.03.097

Maekawa, T., Goto, Y., Kinukawa, N., Taniwaki, T., Kanba, S., & Tobimatsu, S. (2005). Functional characterization of mismatch negativity to a visual stimulus. *Clinical Neurophysiology, 116*(10), 2392-2402. doi:10.1016/j.clinph.2005.07.006

Mann, V. A., & Liberman, I. Y. (1984). Phonological Awareness and Verbal Short-Term Memory. *Journal of Learning Disabilities, 17*(10), 592-599. doi:10.1177/002221948401701005

Masterson, J., Hazan, V., & Wijayatilake, L. (1995). Phonemic processing problems in developmental phonological dyslexia. *Cognitive Neuropsychology, 12*(3), 233-259. doi:10.1080/02643299508251997

Maurer, U., Bucher, K., Brem, S., & Brandeis, D. (2003). Altered responses to tone and phoneme mismatch in kindergartners at familial dyslexia risk. *NeuroReport, 14*(17), 2245-2250. Retrieved from http://journals.lww.com/neuroreport/Fulltext/2003/12020/Altered_responses_to_tone_and_phoneme_mismatch_in.22.aspx

Maurer, U., Bucher, K., Brem, S., & Brandeis, D. (2003). Development of the automatic mismatch response: from frontal positivity in kindergarten children to the mismatch negativity. *Clinical Neurophysiology, 114*(5), 808-817. doi:10.1016/s1388-2457(03)00032-4

Meng, X., Cheng-Lai, A., Zeng, B., Stein, J. F., & Zhou, X. (2011). Dynamic visual perception and reading development in Chinese school children. *Annals of Dyslexia, 61*(2), 161-176. doi:10.1007/s11881-010-0049-2

Mohammed, T., Campbell, R., Macsweeney, M., Barry, F., & Coleman, M. (2006). Speechreading and its association with reading among deaf, hearing and dyslexic individuals. *Clin Linguist Phon, 20*(7-8), 621-630. doi:10.1080/02699200500266745

Molfese, D. L. (1997). Discrimination of language skills at five years of age using event-related potentials recorded at birth. *Dev Neuropsychol, 13*, 135–156. doi:10.1080/87565649709540674

Moll, K., Ramus, F., Bartling, J., Bruder, J., Kunze, S., Neuhoff, N., . . . Landerl, K. (2014). Cognitive mechanisms underlying reading and spelling development in five European orthographies. *Learning and Instruction, 29*, 65-77. doi:10.1016/j.learninstruc.2013.09.003

Mueller, J. L., Friederici, A. D., & Männel, C. (2012). Auditory perception at the root of language learning. *PNAS, 109*(39), 15953-15958. doi:10.1073/pnas.1204319109

Näätänen, R. (1995). The Mismatch Negativity: A Powerful Tool for Cognitive Neuroscience. *Ear & Hearing, 16*(1), 6-18.

Näätänen, R., Gaillard, A. W. K., & Mäntysalo, S. (1978). Early Selective-Attention Effect on Evoked Potential Reinterpreted*. *Acta Psychologica, 42*, 313-329.

Näätänen, R., Paavilainen, P., Rinne, T., & Alho, K. (2007). The mismatch negativity (MMN) in basic research of central auditory processing: a review. *Clinical Neurophysiology, 118*(12), 2544-2590. doi:10.1016/j.clinph.2007.04.026

Näätänen, R., Paavilainen, P., Tiitinen, H., Djiang, D., & Alho, K. (1993). Attention and mismatch negativity. *Psychophysiology, 30*(5), 436-450. doi:10.1111/j.1469-8986.1993.tb02067.x

Neil, P. A., Chee-Ruiter, C., Scheier, C., Lewkowicz, D. J., & Shimojo, S. (2006). Development of multisensory spatial integration and perception in humans. *Developmental Science, 9*(5). doi:10.1111/j.1467-7687.2006.00512.x

Neuhoff, N., Bruder, J., Bartling, J., Warnke, A., Remschmidt, H., Müller-Myhsok, B., & Schulte-Körne, G. (2012). Evidence for the late MMN as a neurophysiological endophenotype for dyslexia. *PLoS One, 7*(5), e34909. doi:10.1371/journal.pone.0034909

Olson, R. K., Rack, J. P., & Conners, F. A. (1991). Eye movements and their heritability in dyslexic and normal readers. In R. Schmid & D. Zambarabier (Eds.), *Oculomotor control and cognitive processes* (pp. 503-513). Amsterdam: North-Holland.

Paul, I., Bott, C., Heim, S., Wienbruch, C., & Elbert, T. R. (2006). Phonological but not auditory discrimination is impaired in dyslexia. *Eur J Neurosci, 24*(10), 2945-2953. doi:10.1111/j.1460-9568.2006.05153.x

Pekkola, J., Laasonen, M., Ojanen, V., Autti, T., Jaaskelainen, I. P., Kujala, T., & Sams, M. (2006). Perception of matching and conflicting audiovisual speech in dyslexic and fluent readers: an fMRI study at 3 T. *Neuroimage, 29*(3), 797-807. doi:10.1016/j.neuroimage.2005.09.069

Perfetti, C. A. (1999). Comprehending written language: A blueprint of the reader. In C. M. Brown & P. Hagoort (Eds.), *The neurocognition of language* (pp. 167-208). Oxford: University Press.

Pihko, E., Leppänen, P. H. T., Eklund, K. M., Cheour, M., Guttorm, T. K., & Lyytinen, H. (1999). Cortical responses of infants with and without a genetic risk for dyslexia: I. Age effects. *NeuroReport, 10*(5), 901-905. Retrieved from http://journals.lww.com/neuroreport/Fulltext/1999/04060/Cortical_responses_of_infants_with_and_without_a.2.aspx

Ponton, C. W., Bernstein, L. E., & Auer, E. T., Jr. (2009). Mismatch negativity with visual-only and audiovisual speech. *Brain Topogr, 21*(3-4), 207-215. doi:10.1007/s10548-009-0094-5

Pugh, K. R., Mencl, W. E., Jenner, A. R., Katz, L., Frost, S. J., Ren Lee, J., . . . Shaywitz, B. A. (2001). Neurobiological studies of reading and reading disability. *Journal of Communication Disorders, 34*(479-492).

Quandt, D. (2004). *Ereigniskorrelierte Potenziale und Mismatch Negativity zur Objektivierung vorbewusster Phonem- und Tonhöhendiskrimination bei unauffälligen Säuglingen*. (Phd), Freie Universität Berlin. Retrieved from www.diss.fu-berlin.de/2004/252/indexe.html

Ramus, F., Rosen, S., Dakin, S. C., Day, B. L., Casellote, J. M., White, S., & Frith, U. (2003). Theories of developmental dyslexia: insights from a multiple case study of dyslexic adults. *Brain, 126*, 841-865. doi:10.1093/brain/awg076

Restuccia, D., Della Marca, G., Marra, C., Rubino, M., & Valeriani, M. (2005). Attentional load of the primary task influences the frontal but not the temporal generators of mismatch negativity. *Cognitive Brain Research, 25*(3), 891-899. doi:10.1016/j.cogbrainres.2005.09.023

Rugg, M. D., & Coles, M. G. H. (1995). *Electrophysiology of mind: Event-related brain potentials and cognition*. New York: Oxford University Press.

Ruhnau, P., Wetzel, N., Widmann, A., & Schröger, E. (2010). The modulation of auditory novelty processing by working memory load in school age children and adults: a combined behavioral and event-related potential study. *BMC Neurosci, 11*, 126. doi:10.1186/1471-2202-11-126

Salmelin, R., Service, E., Kiesilä, P., Uutela, K., & Salonen, O. (1996). Impaired Visual Word Processing in Dyslexia Revealed with Magnetoencephalography. *Annals of Neurology, 40*(2), 157-162. doi:10.1002/ana.410400206

Samuelson, S., & Lundberg, I. (2003). The Impact of Enbironmental Factors on Components of Reading and Dyslexia. *Annals of Dyslexia, 53*(1), 201-217.

Scerri, T. S., & Schulte-Körne, G. (2010). Genetics of developmental dyslexia. *Eur Child Adolesc Psychiatry, 19*(3), 179-197. doi:10.1007/s00787-009-0081-0

Schneider, W., Schlagmüller, M., & Ennemoser, M. (2007). *LGVT 6-12: Lesegeschwindigkeits-und-verständnistest für die Klassen 6-12*: Hogrefe.

Schröger, E., & Winkler, I. (1995). Presentation rate and magnitude of stimulus deviance effects on human pre-attentive change detection. *Neurosci Lett, 193*, 185-188.

Schulte-Körne, G. (2001). *Lese-Rechtschreibstörung und Sprachwahrnehmung: psychometrische und neurophysiologische Untersuchungen zur Legasthenie*: Waxmann.

Schulte-Körne, G., & Bruder, J. (2010). Clinical neurophysiology of visual and auditory processing in dyslexia: a review. *Clin Neurophysiol, 121*(11), 1794-1809. doi:10.1016/j.clinph.2010.04.028

Schulte-Körne, G., Deimel, W., Bartling, J., & Remschmidt, H. (1998). Auditory processing and dyslexia: evidence for a specific speech processing deficit. *NeuroReport, 9*, 337-340.

Schulte-Körne, G., Deimel, W., Bartling, J., & Remschmidt, H. (2001). Speech perception deficit in dyslexic adults as measured by mismatch negativity (MMN). *International Journal of Psychophysiology, 40*, 77-87.

Schulte-Körne, G., & Remschmidt, H. (2003). Legasthenie-Symptomatik, Diagnostik, Ursachen, Verlauf und Behandlung. *Deutsches Ärzteblatt, 7*, A396-A406.

Shaywitz, S. E., & Shaywitz, B. A. (2008). Paying attention to reading: the neurobiology of reading and dyslexia. *Dev Psychopathol, 20*(4), 1329-1349. doi:10.1017/S0954579408000631

Shestakova, A., Brattico, E., Huotilainen, M., Galunov, V., Soloviev, A., Sams, M., . . . Näätänen, R. (2002). Abstract phoneme representations in the left temporal cortex: magnetic mismatch negativity study. *NeuroReport, 13*(14), 1813-1816.

Snowling, M. J. (1998). Dyslexia as a Phonological Deficit: Evidence and Implications. *Child Psychology & Psychiatry, 3*(1), 4-11.

Squires, N. K., Squires, K. C., & Hillyard, S. A. (1975). Two varieties of long-latency positive waves evoked by unpredictable auditory stimuli in man. *Electroencephalography and clinical Neurophysiology, 38*, 387-401. doi:10.1016/0013-4694(75)90263-1

Stark, L. W., Giveen, S. C., & Terdiman, J. F. (1991). Specific dyslexia and eye movements. *Vision and visual dyslexia*, 203-232.

Stein, J. (2001). The magnocellular theory of developmental dyslexia. *Dyslexia, 7*(1), 12-36. doi:10.1002/dys.186

Stein, J., & Walsh, V. (1997). To see but not to read; the magnocellular theory of dyslexia. *Trends Neurosci, 20*(4), 147-152. doi:10.1016/S0166-2236(96)01005-3

Stock, C., Marx, P., & Schneider, W. (2003). *Basiskompetenzen für Lese-Rechtschreibleistung (test for basic competences for reading and spelling)*. Göttingen: Beltz Test GmbhH.

Stock, C., & Schneider, W. (2008). *Deutscher Rechtschreibtest (DERET) (German spelling test)*. Göttingen: Hogrefe.

Talcott, J. B., Gram, A., Van Ingelghem, M., Witton, C., Stein, J. F., & Toennessen, F. E. (2003). Impaired sensitivity to dynamic stimuli in poor readers of a regular orthography. *Brain and Language, 87*(2), 259-266. doi:10.1016/s0093-934x(03)00105-6

Tallal, P., Miller, S., & Fitch, R. H. (1993). Neurobilogical Basis of Speech: A Case for the Preeminence of Temporal Processing. *Annals of the New York* *academy of sciences, 682*(1), 27-47. doi:10.1111/j.1749-6632.1993.tb22957.x

Teinonen, T., Aslin, R. N., Alku, P., & Csibra, G. (2008). Visual speech contributes to phonetic learning in 6-month-old infants. *Cognition, 108*(3), 850-855. doi:10.1016/j.cognition.2008.05.009

van Atteveldt, N., Formisano, E., Goebel, R., & Blomert, L. (2004). Integration of letters and speech sounds in the human brain. *Neuron, 43*(2), 271-282. doi:10.1016/j.neuron.2004.06.025

van Wassenhove, V., Grant, K. W., & Poeppel, D. (2005). Visual speech speeds up the neural processing of auditory speech. *Proc Natl Acad Sci U S A, 102*(4), 1181-1186. doi:10.1073/pnas.0408949102

Vellutino, F. R. (1987). Dyslexia. *Scientific American, 256*(3), 34-41. doi:10.1038/scientificamerican0387-34

Vellutino, F. R., Fletcher, J. M., Snowling, M. J., & Scanlon, D. M. (2004). Specific reading disability (dyslexia): what have we learned in the past four decades? *Journal of Child Psychology and Psychiatry, 45*(1), 2-40. doi:10.1046/j.0021-9630.2003.00305.x

Virsu, V., Lahti-Nuuttila, P., & Laasonen, M. (2003). Crossmodal temporal processing acuity impairment aggravates with age in developmental dyslexia. *Neurosci Lett, 336*(3), 151-154. doi:10.1016/s0304-3940(02)01253-3

von Suchodoletz, W. (2010). Concepts of therapy for children with dyslexia. *Z Kinder Jugendpsychiatr Psychother, 38*(5), 329-327; quiz 338-329. doi:10.1024/1422-4917/a000057

Wagner, R. K., & Trogensen, J. K. (1987). The nature of phonological processing and its causal role in the acquisition of reading skills. *Psychol Bull, 101*, 192–212. doi:10.1037/0033-2909.101.2.192

Wetzel, N., Berti, S., Widmann, A., & Schröger, E. (2004). Distraction and reorientation in children: a behavioral and ERP study. *NeuroReport, 15*(8), 1355-1358. doi:10.1097/01.wnr.0000129858.40478.be

WorldMedicalAssociation. (2013). World medical association declaration of helsinki: Ethical principles for medical research involving human subjects.

JAMA, 310(20), 2191-2194. doi:10.1001/jama.2013.281053

Zaehle, T., Wustenberg, T., Meyer, M., & Jancke, L. (2004). Evidence for rapid auditory perception as the foundation of speech processing: a sparse temporal sampling fMRI study. *Eur J Neurosci, 20*(9), 2447-2456. doi:10.1111/j.1460-9568.2004.03687.x

List of Figures

Abbreviations

aMMR .... auditory Mismatch Response

ANOVA .... analysis of variance

ANCOVA .... analysis of covariance

DD .... developmental dyslexia

EEG .... electroencephalography

ERP .... event-related potential

IFG .... inferior frontal gyrus

PCA .... principal component analysis

STG .... superior temporal gyrus

STS .... superior temporal sulcus

vaMMR .... visual-auditory Mismatch Response

vMMR .... visual Mismatch Response

WP .... writing problems

Appendix A – Study I

Schaadt, G., Männel, C., van der Meer, E., Pannekamp, A., Oberecker, R., & Friederici, A. D. (2015). Present and past: Can writing abilities in school children be associated with their auditory discrimination capacities in infancy?. *Research in Developmental Disabilities, 47*. 318–333. doi: 10.1016/j.ridd.2015.10.00

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Present and past: Can writing abilities in school children be associated with their auditory discrimination capacities in infancy?

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ABSTRACT

Literacy acquisition is highly associated with auditory processing abilities, such as auditory discrimination. The event-related potential Mismatch Response (MMR) is an indicator for cortical auditory discrimination abilities and it has been found to be reduced in individuals with reading and writing impairments and also in infants at risk for these impairments. The goal of the present study was to analyze the relationship between auditory speech discrimination in infancy and writing abilities at school age within subjects, and to determine when auditory speech discrimination differences, relevant for later writing abilities, start to develop. We analyzed the MMR registered in response to natural syllables in German children with and without writing problems at two points during development, that is, at school age and at infancy, namely at age 1 month and 5 months. We observed MMR related auditory discrimination differences between infants with and without later writing problems, starting to develop at age 5 months–an age when infants begin to establish language-specific phoneme representations. At school age, these children with and without writing problems also showed auditory discrimination differences, reflected in the MMR, confirming a relationship between writing and auditory speech processing skills. Thus, writing problems at school age are, at least, partly grounded in auditory discrimination problems developing already during the first months of life.

1. Introduction

Reading and writing are two of the most important cultural abilities, not only for children during schooling, but also for later everyday life challenges. According to the Diagnostic and Statistical Manual of Mental Disorders: DSM-V (American Psychiatric Association, 2013), impairments in reading and/or writing belong to the category of specific learning disorders (SLD) and occur in 4–5% of German school children (Schulte-Körne & Remschmidt, 2003). SLD are diagnosed if reduced

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Appendix B – Study II

Schaadt, G., Männel, C., van der Meer, E., Pannekamp, A., & Friederici, A. D. (2015). Facial speech gestures: The relation between visual speech processing, phonological awareness, and developmental dyslexia in 10-year-olds. *Developmental Science, Article first published online*, 1–15. doi: 10.1111/desc.12346

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PAPER

Facial speech gestures: the relation between visual speech processing, phonological awareness, and developmental dyslexia in 10-year-olds

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Abstract

Successful communication in everyday life crucially involves the processing of auditory and visual components of speech. Viewing our interlocutor and processing visual components of speech facilitates speech processing by triggering auditory processing. Auditory phoneme processing, analyzed by event-related brain potentials (ERP), has been shown to be associated with impairments in reading and spelling (i.e. developmental dyslexia), but visual aspects of phoneme processing have not been investigated in individuals with such deficits. The present study analyzed the passive visual Mismatch Response (vMMR) in school children with and without developmental dyslexia in response to video-recorded mouth movements pronouncing syllables silently. Our results reveal that both groups of children showed processing of visual speech stimuli, but with different scalp distribution. Children without developmental dyslexia showed a vMMR with typical posterior distribution. In contrast, children with developmental dyslexia showed a vMMR with anterior distribution, which was even more pronounced in children with severe phonological deficits and very low spelling abilities. As anterior scalp distributions are typically reported for auditory speech processing, the anterior vMMR of children with developmental dyslexia might suggest an attempt to anticipate potentially upcoming auditory speech information in order to support phonological processing, which has been shown to be deficient in children with developmental dyslexia.

Research highlights

- Visual phoneme processing of mouth movements tested by analyzing visual Mismatch Response (vMMR) in school children with and without developmental dyslexia.
- Children without developmental dyslexia exhibit a posterior vMMR, whereas children with developmental dyslexia show an anterior vMMR, normally reported for auditory phoneme processing.
- Anterior vMMR was even more pronounced in children with severe phonological deficits, suggesting an attempt to compensate for their phonological deficit.

Introduction

One of the key features of speech is that it is naturally a multisensory phenomenon and both auditory and visual information are crucially involved (Benoît, Guiard-Marigny, Goff & Adjoudani, 1996). Seeing the interlocutor's face aids or can even partially replace the processing of auditory information. This is especially true in difficult auditory communication conditions such as noisy environments (Bernstein, Auer & Takayanagi, 2004) and during second language learning (Navarra & Soto-Faraco, 2007), but also during clearly audible and intact speech (Arnold & Hill, 2001). During speech perception, visual information (i.e. lip and mouth

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Appendix C – Study III

Schaadt, G., Männel, C., van der Meer, E., Pannekamp, A., Oberecker, R., & Friederici, A. D. (in preparation). Deficient visual-auditory speech processing in elementary school children with limited spelling abilities: When crossmodal integration goes wrong independent of letter knowledge.

Deficient visual-auditory speech processing in elementary school children with limited spelling abilities: When crossmodal integration goes wrong independent of letter knowledge

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During information processing, individuals benefit from bimodally presented information, as demonstrated for the processing of letter-speech sound pairs. While this was found for typically developing individuals, school children with reading and spelling problems do not show this bimodal benefit, suggesting deficient integration of visual (letters) and auditory (speech sounds) information. However, this finding does not allow differentiating between a general deficit of integrating visual-auditory information of spoken expression that might arise during early development independent of children's reading and spelling, and an integration deficit that is specific to letter-speech sound pairs and which develops when children learn to read and write. We examined whether school children with spelling problems exhibit deficient visual-auditory speech processing of video-recorded mouth movements pronouncing syllables. Our results show that school children with and without spelling problems process visual-auditory speech stimuli similarly as revealed by the event-related potential Mismatch Response. However, a principal component analysis of the Mismatch Response revealed differences for children with and without spelling problems, suggesting a general speech integration deficit for children with spelling problems. Therefore, children with spelling problems might exhibit a specific speech integration deficit, potentially causing letter-speech sound integration problems during reading and spelling acquisition.

Keywords: visual-auditory speech processing, visual-auditory Mismatch Response, spelling abilities, school children; German language

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