FACULTY OF PSYCHOLOGY
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# TESTING THE INTERHEMIPHERIC TRANSFER DEFICIT THEORY IN DYSLEXIA USING A LEXICAL DECISION TASK

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**Abstract**

The interhemispheric transfer deficit theory proposes that people with dyslexia have impaired interhemispheric transfer, resulting in difficulties with processing words in the left visual field (LVF). This can be studied with a visual half-field task. Participants with dyslexia showed an increased right visual field (RVF) advantage and a reduced redundant bilateral advantage (RBA), which can be explained by poorer accuracy to words in the LVF (Bradshaw et al., 2020; Henderson et al., 2007). The aim of the current study was to test the interhemispheric transfer deficit in dyslexia by using a lexical decision task. Reaction times, which have not been included before in this line of research, were also considered as a measure to reflect cognitive processing speed. The results showed no increased RVF advantage or decreased RBA in the dyslexia group based on neither accuracy nor reaction times, which is inconsistent with previous studies (Bradshaw et al., 2020; Henderson et al., 2007). A possible explanation for the deviating results is that the used lexical decision task might involve different cognitive processes than the original task, which required word reproduction. This raises the question for which language processes an interhemispheric transfer deficit can be observed in dyslexia. This study also proposes a possible link with the corpus callosum, which shows structural differences in people with dyslexia (Paul, 2010). The location of these neuroanatomical differences might be related to which cognitive processes are affected by impaired hemispheric transfer in dyslexia. This should be considered in further research.

**Nederlandse Samenvatting**

De interhemisferische overdrachtsbeperkingstheorie (interhemispheric transfer deficit) stelt dat mensen met dyslexie een aangetaste interhemisferische overdracht hebben, wat uitloopt in moeilijkheden met het verwerken van woorden die in het linker visuele veld (LVV) worden waargenomen. Dit kan onderzocht worden met visuele halfveldtaken. Participanten met dyslexie hebben een vergroot voordeel voor het rechter visuele veld (RVV) en een verminderd redundant bilateraal voordeel (RBV), wat kan verklaart worden door verminderde accuratesse voor woorden in het LVV (Bradshaw et al., 2020; Henderson et al., 2007). Het doel van de huidige studie was om de interhemisferische overdrachtsbeperkingstheorie te onderzoeken aan de hand van een lexicale beslissingstaak. Reactietijden, die in deze onderzoekslijn nog niet eerder werden onderzocht, werden ook gemeten als een reflectie van mentale verwerkingssnelheid. Uit de resultaten gebaseerd op de accuratesse en reactietijden, bleek de dyslexiegroep geen verhoogd RVV-voordeel of verminderde RBV te hebben, wat niet consistent is met vorig onderzoek (Bradshaw et al., 2020; Henderson et al., 2007). Een mogelijke verklaring voor deze afwijkende resultaten is dat de gebruikte lexicale beslissingstaak andere cognitieve processen omvat dan de oorspronkelijke taak, die woordreproductie betrof. Dit roept de vraag op bij welke taalprocessen een aangetaste interhemisferische overdracht kan worden waargenomen bij dyslexie. Dit onderzoek stelt ook een mogelijk verband voor met het corpus callosum, wat structureel verschillend kan zijn bij mensen met dyslexie (Paul, 2010). De locatie van deze neuroanatomische verschillen kan gerelateerd zijn aan welke cognitieve processen worden beïnvloed door verminderde hemisferische overdracht bij dyslexie. Dit moet nog verder worden onderzocht.

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**Table of Contents**

**Testing the Interhemispheric Transfer Deficit Theory in Dyslexia Using a Lexical Decision Task**

## Dyslexia

Dyslexia, also referred to as developmental dyslexia, is a common neurodevelopmental learning disorder, recognized by persistent difficulties in reading and spelling (Lyon et al., 2003). These reading problems express themselves as difficulties with identifying written words and with fluent reading (Lefly & Pennington, 1991). Children often have trouble learning to read and write, but when these difficulties persist beyond expected difficulties based on their educational level, it might be an indication of dyslexia (Lyon et al., 2003). For that reason, it is mostly diagnosed in early school-aged children. Yet, it is possible that it only gets picked up on in adulthood, when required reading and spelling skills for school or work become more complex (American Psychiatric Association, 2013). People with dyslexia do not only experience problems with reading and spelling. Dyslexia is also characterized by impaired decoding (Bernstein, 2008), which is the ability to match letters or series of letters to their corresponding sounds. People with dyslexia often experience difficulties with this (Bernstein, 2008). For example, they have trouble pronouncing pseudowords (a string of letters that looks like a word, but has no semantic meaning), because it is difficult for them to transform the unfamiliar spelling into the correct sounds (Brunswick et al., 1999).

As dyslexia is characterized by decoding problems, prevalence is dependent on the transparency of a language (Jiménez et al., 2009; van Vreckem & Desoete, 2018). Transparency is the accordance between the orthography and the phonology of the language (Lété et al., 2008). Some languages, like Spanish, are more transparent and are easier to decode. Transparent languages have unambiguous letter, or letter group, to sound mapping (Defior et al., 2009). Certain letters have a certain pronunciation and certain sounds are written a certain way, without many exceptions. About 3 to 6% of the Spanish are estimated to have dyslexia (Soriano-Ferrer & Morte-Soriano, 2017). English, however, is a very untransparent, or opaque, language (Verhoeven et al., 2006). There are many ways to pronounce certain letters. English even contains heteronyms, which are words that are spelled the same but have different pronunciations and meanings. For example, the noun ‘present’, meaning a gift, is pronounced *ˈprɛznt*, but the verb ‘to present’, meaning to give, is pronounced *prɪˈzɛnt*. Additionally, there are many ways to spell the same sound; think of ‘their’, ‘they’re’, and ‘there’, three words all pronounced the same way, but spelled differently. With such a complicated letter-to-sound mapping, the prevalence of dyslexia in English-speaking populations is estimated to be about 15 to 20% (International Dyslexia Association, 2020). Dutch is an in-between case: there are a few ambiguities like the words ‘geval’, pronounced *xəˈval*, and ‘gevel’, pronounced *ˈxevəl*, but not as many as in English. Prevalence is estimated between 5 to 7% (Hellinckx & Ghesquière, 2005).

***Diagnosis of Dyslexia***

Part of why prevalence differs between countries is also a result of the varying definitions and criteria for diagnosis that different countries and organizations handle. According to the Diagnostic and Statistical Manual of Mental Disorders, Fifth Version (DSM-5), of the American Psychiatric Association (2013), dyslexia is categorized as a specific learning disorder. Specific learning disorders are described as persistent difficulties with learning and using academic skills for at least 6 months, despite interventions targeting these difficulties. Academic skills are below what would be expected of someone of the same age. The difficulties start during school-age and are not caused by any other conditions, such as non-corrected visual impairments or general cognitive impairment. A distinction is made between difficulties regarding reading, difficulties with written expression, and difficulties with mathematical skills. The DSM-5 places dyslexia under the term 'difficulties regarding reading' and describes it as 'learning difficulties due to problems with accurate and fluent word recognition, impaired decoding and impaired spelling skills' (American Psychiatric Association, 2013, p. 120).

Flanders also has their own set of diagnostic criteria for the diagnosis of dyslexia, as described by Network Learning Problems Flanders (Ghesquière, 2014). Three conditional criteria can be distinguished: the severeness criterion, the mild exclusion criterion, and the didactic resistance criterion (loosely translated from Dutch). The severeness criterion states that reading and/or spelling abilities need to be seriously impaired in order for the person to be diagnosed with dyslexia. People need to score significantly lower than what would be expected of someone of the same age, and this is tested with Flemish-validated tests. The problems with reading and/or spelling should also not be the consequence of any other disorder, as declared by the mild exclusion criterion. Lastly, according to the didactic resistance criterion, the impairments should persevere despite interventions specifically targeting these problems. After clinical intervention, people with dyslexia still score unusually low. In Flanders, all 3 criteria must be met to be diagnosed with dyslexia.

Even though the mild exclusion criterion states that dyslexia may not be the cause of any other underlying disability, it must be stressed that this does not deny the comorbid character of the disorder. Dyslexia often co-occurs with other neurodevelopmental disorders like Attention Deficit Hyperactivity Disorder (ADHD), dyscalculia, and Developmental Coordination Disorder (DCD). Twelve to 24% of people with dyslexia also have ADHD (Shaywitz & Shaywitz, 2008). ADHD is a disorder characterized by attention deficits. This might be why it co-occurs so often with dyslexia, as attention mechanisms are involved in reading (Shaywitz & Shaywitz, 2008). The comorbidity of dyslexia and dyscalculia is about 40% (Wilson et al., 2015). An explanation for this could be that the disorders share certain underlying mechanisms, such as verbal working memory (Swanson et al., 2008). Dyslexia and DCD co-occur up to 50% of the time (Federico et al., 2022). DCD is a disorder that affects fine and/or gross motor skills. This comorbidity might exist because motor skills are not only important for learning to write but also to participate in educational practices (Biotteau et al., 2019).

***Etiology of Dyslexia***

As can be assumed from the didactic resistance criterion, there is currently no neurobiological or medical treatment for dyslexia. This is because the exact causes of dyslexia are still unknown. For now, clinical intervention exists of exercises to improve reading skills, to decrease the difficulties experienced in dyslexia (Schulte-Körne, 2010). As with many neurodevelopmental disorders, the underlying mechanisms are most likely of genetic and environmental nature (Peterson & Pennington, 2015). It is known that genetics play a role, because having a family member with dyslexia increases the chance to have dyslexia yourself. Estimations for the inheritance rate range up to 50% (Hohnen & Stevenson, 1999). This means that dyslexia gets passed on through genes in about 50% of the cases. This suggests that parents with dyslexia have a ½ chance that their children will also have dyslexia. Even though it is known that there are genetic factors to dyslexia, it is not yet known which genes exactly are relevant. Genes on chromosome 6 and chromosome 15 might be related (Ghesquière et al., 2011; Snowling, 2000), but the complete genetic makeup of the disorder is yet to be determined.

On the other hand, dyslexia cannot be explained by genetic mutations alone, as environment also is a significant factor. Theodoridou et al. (2021) linked early life stress to dyslexia, and maternal smoking during pregnancy, birth weight, and social economic status (SES) have also been associated with dyslexia by Mascheretti et al. (2011). The authors argue that these influences can all be explained by a poor environment, which is less supportive regarding reading-related behavior. This view is in line with the diathesis-stress model (Rende & Plomin, 1992), claiming that a less supportive environment leads to genetic vulnerabilities manifesting themselves worse than they would in a more supportive environment. Specifically, this would mean that children who are prone to have dyslexia because of their genes are more likely to develop symptoms when they live in a less supportive environment (Mascheretti et al., 2011).

These genetic and environmental factors also have an influence on the neuroanatomy of people with dyslexia. Researchers have conducted neuroimaging studies to explore the role of brain volume and function in dyslexia. From studies on postmortem brains (Galaburda et al., 1985) and studies using diffusion tensor imaging (Klingberg, 2002), it is known that the left temporo-parietal-occipital brain regions of dyslectic patients typically contain less white and gray matter volume. In addition, multiple functional neuroimaging studies (such as functional magnetic resonance imaging [fMRI] and magnetoencephalography [MEG]) show reduced activation in the left hemisphere of people with dyslexia during reading tasks (Nora et al., 2021; Richlan, 2012; Shaywitz et al., 2003; Simos et al., 2000). There is also indication for stronger activation of the right hemisphere during reading tasks as compared to a control group, perhaps as a compensation for the lesser left activation (Pagnotta et al., 2015; Pugh et al., 2001).

***Theoretical Models of Dyslexia***

Multiple theoretical approaches to developmental dyslexia have been proposed over the years to try to explain how these neuroanatomical abnormalities can cause dyslexia. For example, there are theories based on deficits in the visual system, like unstable binocular fixations (Eden et al., 1994) or difficulties with focusing on a target that is presented in a clutter, like letters in a word (Spinelli et al., 2002). These theories stem from the fact that non-verbal deficits in visual tasks can also occur in people with dyslexia (Marinelli et al., 2011). A major theory that focuses on the visual system is the magnocellular deficit theory (Stein, 2001). This theory claims that reduced sensitivity of the magnocellular pathway of the visual system is the underlying cause of dyslexia. The magnocellular pathway is responsible for rapid communication between the retina and the occipital and parietal areas (Greatrex & Drasdo, 1995). Stein et al. (2000) argue that reduced sensitivity in this pathway makes it harder to quickly detect visual stimuli, which can result in the type of reading problems that dyslexia is characterized by.

Another theory that looks for an explanation beyond deficits in the brain areas related to language, is the cerebellar deficit theory. The cerebellum is not only responsible for learning motor skills but is also believed to play a role in the automatization of tasks (Nicolson & Fawcett, 2010). Reduced activity in the right cerebellum of dyslectics has been shown to be related to the impairment of automatic processes like reading or decoding (Nicolson et al., 1999). The fact that people with dyslexia sometimes also perform worse on certain tasks requiring cerebellar activation, like motor tasks or time estimation (Fawcett & Nicolson, 1995; Nicolson et al., 1995), is also consistent with this theory. Another imaging study also showed reduced brain volume in the cerebellum of people with dyslexia (Eckert, 2003).

Nowadays it is more or less accepted that dyslexia is the consequence of language deficits, mainly in phonology. Other impairments like non-verbal or motor problems are more likely the cause of comorbidity of dyslexia with other disorders (Ramus, 2003a). The phonological deficit theory proposes difficulties in representing, storing, and retrieving phonemes as the underlying cause of dyslexia. People with dyslexia experience problems with, among other, phonological processing, like linking graphemes (a letter or a group of letters that represent a sound) with their corresponding sounds (phonemes; Snowling, 1981). Ramus (2004) argues that phonological processing also affects lexical retrieval. Because the processing of language is dependent on phonological awareness, verbal short-term memory, and lexical retrieval, impairment in these functions could explain the symptoms of dyslexia. In a multiple case study of Ramus (2003b), all 16 dyslectics showed phonological impairment, of which 10 participants also displayed auditory deficits, only four displayed motor problems, and two visual magnocellular problems. These results indicate the central role phonological impairment might play in developmental dyslexia.

Even though the phonological deficit theory is a widely accepted theory, not all people with dyslexia experience problems with phonological processing. To explain this dissociation, Wolf and Bowers (2000) proposed an extension to the theory: the double deficit theory. On top of problems with phonological processing, they suggested that dyslexia sometimes also comes with problems in rapid serial or automatic naming. This theory was based on the robust finding that, on top of phonological impairments, children and adults with dyslexia often also have slower reaction times in naming speed tasks compared to control participants (see Wolf et al., 2000, for a review). The double deficit theory differentiates between three subtypes of dyslexia: people who have problems with phonological processing, people who have problems with rapid serial naming, and people who have problems with both. According to them, people with phonological processing problems are especially deficient in decoding accuracy, and people with rapid serial naming problems lack reading fluency. Logically, people with a double deficit should experience more severe symptoms. Lovett et al. (2000) did indeed find that when they categorized a group of 116 children with reading impairments according to these three subtypes, the children with both deficits exhibited more severe symptoms as assessed by multiple measures of reading development and language acquisition.

**Typical Language Comprehension**

Dyslexia differs from normal language comprehension. But to compare language processes in dyslexia with typical language comprehension, it is essential to know how language is typically processed, in particular written text. To understand normal language processing in the brain, many functional imaging studies have been performed since the 1990s. Gernsbacher and Kaschak (2003) reviewed 15 years of imaging studies and concluded that various regions dispersed in the brain are involved in language processing. This is a brief overview of the areas related to reading:

Essential for reading is orthographic processing, or the processing of written words. Pugh et al. (1996) linked activation in the left lateral extrastriate regions with orthographic processing. The occipital-temporal sulcus and the posterior inferior-temporal regions are also related to orthographic processing. These areas show bilateral activation during the presentation of letters and pseudocharacters, indicating early visual linguistic processing (Fujimaki et al., 1999).

Besides orthographic processing, visual words are also believed to be transformed into phonological representations (Xu, 2001). Phonological processing in the translation of written words to sounds. This process has been linked with activation in the left superior temporal gyrus, or Wernicke's area, and the surrounding areas like the left supramarginal gyrus and the angular gyrus (Small et al., 1996; Xu,2001).

In tasks where participants need to access semantics, like judging whether a word is abstract or concrete, the left inferior frontal gyrus, the left cingulate cortex, and the left superior frontal region are activated (Demb et al., 1995). When participants are asked to come up with words given a certain clue or starting letter, the left inferior frontal regions, and the areas around Wernicke's area and the left superior frontal gyrus show activation (Cuenod et al., 1995). Activation in the superior frontal regions and the right cerebellum have also been linked to these tasks (Phelps et al., 1997; Schlosser et al., 1998). Remarkable is that the generation of verbs shows stronger activation in Broca's area, namely the left inferior frontal gyrus, and the surrounding areas compared to noun generation (Weiller et al., 1995).

In short, visual words are first processed in the occipital lobe, where the visual cortex is located. Activation then spreads to the boundary between the left occipital and temporal lobes for orthographic and phonological processing. Processing on the word-level seems to involve especially the left inferior frontal regions and the left posterior temporal regions around Wernicke's area (Gernsbacher & Kaschak, 2003).

**Lateralization**

As mentioned, most of the areas involved in written word processing are located in the left hemisphere. This corresponds with the concept of lateralization. The idea of lateralization of brain functions is that certain cognitive abilities are performed dominantly by one hemisphere of the brain, which is why lateralization is also referred to as hemispherical lateralization (Gazzaniga, 1995). Few functions rely entirely on a single area of the brain, but they can rely more on one area and thereby one hemisphere, than the other. For example, language, praxis, and calculation mainly activate areas in the left hemisphere, while spatial attention, face recognition, and prosody of speech rely more on the right hemisphere (Vingerhoets, 2019).

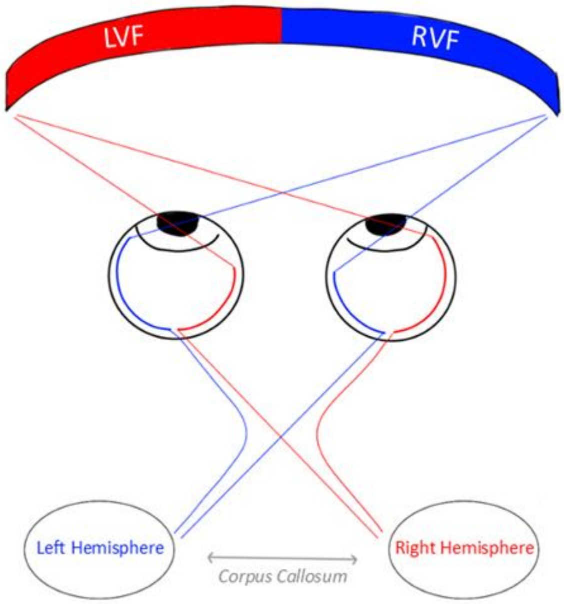
***The Visual Half-Field Task***

As demonstrated in language processing, the golden standard to study lateralization is functional brain imaging, in particular fMRI. This is however an expensive method. The visual half-field task is a less costly way to study lateralization (Hellige, 1993), which uses behavioral measures like reaction times to study lateralization. Visual half-field tasks are based on the fact that visual information is initially processed bilaterally, in both hemispheres (Jeffery, 2001). In particular the visual field is projected contralateral on the visual cortex. This means that information from the right side of the visual field (RVF) is projected in the left visual cortex and information from the left visual field (LVF) is projected in the right visual cortex, as can be seen in Figure 1.

The contralateral projection of the visual field allows us to study the lateralization of language using visual half-field tasks (Hellige, 1993). By presenting words in either the RVF or LVF, it

**Figure 1**

*The Contralateral Projection of the Visual Field*




*Note*: Schematic of the contralateral projection of the visual field. Information observed in the left visual field (LVF) is projected on the right hemisphere, and information in the right visual field (RVF) is projected on the left hemisphere. Both hemispheres are connected through the corpus callosum. Based on Figure 1 '*Models of hemispheric interactions involved in word recognition*.' by Bradshaw et al. (2020).

can be controlled in which hemisphere the visual properties of these words are initially projected, namely the contralateral one. An important aspect is that both hemispheres are connected through the corpus callosum, a large bundle of fibers, which allows for the interhemispheric transfer of information. According to the colossal relay hypothesis (Steinmann et al., 2017), transferring information from one hemisphere to the other through the corpus callosum causes a delay. This means that when visual information has to be transferred through the corpus callosum to the other hemisphere where it can be processed further, the total processing time of a word will be longer. If there is a difference in the processing time of words in the RVF in contrast with the LVF, it is possible to deduce in which hemisphere the words are being processed by comparing reaction times.

***The Right Visual Field Advantage***

From studies using the visual half-field (VHF) task, it is known that the RVF has an advantage over the LVF in processing words (Barca et al., 2011; Bourne, 2006; Hellige, 1993). As mentioned, language understanding typically relies more on the left hemisphere of the brain. As a consequence of this distribution of lateralization, words that are perceived in the left visual field have to be transferred from the right hemisphere to the left hemisphere before they can be processed further.

This interhemispheric transfer process will lead to a longer processing time. On the other hand, words perceived in the RVF will be projected directly on the left hemisphere, where they immediately will be processed. Hence words in the RVF have an advantage over words in the LVF. This phenomenon has been reported by multiple behavioral studies (Barca et al., 2011; Bourne, 2006; Hellige, 1993). Words presented in the RVF are not only reported faster but also more accurately (Barca et al., 2011; Hellige, 1993). These words are additionally distinguished faster from non-words and evaluated faster by meaning (Bourne, 2006).

A second phenomenon that can be observed with VHF tasks is that the bilateral presentation of stimuli can also improve performance. This is known as the redundant bilateral advantage (RBA; Hellige, 1993). Seeing a word in both visual fields induces faster reaction times than seeing a word in the RVF only (Marks & Hellige, 1999). So even though the RVF has an advantage over the LVF in unilateral presentations of stimuli, processing a stimulus that was visible in both visual fields will typically be quicker. The faster reaction times can be explained by the added information from the LVF that is initially projected on the right hemisphere, and then transferred through the corpus callosum to the left hemisphere, while the left hemisphere is still processing the input from the RVF. This additional information contributes to the lexical processing of a word in the left hemisphere, leading to faster reaction times than in unilateral presentation (Marks & Hellige, 1999).

Another possible explanation would be that the faster reaction times are due to a race between the two hemispheres, where two simultaneous sets of processing are happening and the one with the fastest processing time 'wins' (Miller, 1982). However, Henderson et al. (2007) discarded this theory by presenting partial cues to words in one visual field and the whole word in the other visual field. They observed faster identification of the words when the partial cues were given than when a word was presented in one visual field only, without partial cues. Since the difficulty of identifying a word based on only the partial cues, it was not very likely that the faster reaction times were due to a race between the hemispheres, but rather that the summation of the input of both visual fields facilitated the processing of the words.

Another indication against this race theory is that split-brain patients do not experience this effect because their corpus callosum is severed (Mohr et al., 1994). This should not matter for the race theory as both hemispheres process the stimuli separately. However, the absence of the RBA in split-brain patients can be explained by the first given explanation regarding cooperation between the hemispheres, as, due to the severed corpus callosum, information from the LVF is not able to reach the left hemisphere and enhance the processing.

**Dyslexia and the Interhemispheric Transfer Deficit**

Henderson et al. (2007) and Bradshaw et al. (2020) used a VHF task to study interhemispheric transfer in people with dyslexia. They presented words in the LVF, the RVF, or bilaterally while the participants were instructed to focus on a fixation cross in the center of the screen. The central fixation discouraged participants to make eye movements towards the presented words, which ensured that words were actually presented in the relevant half-field. The participants were asked to perform a word reproduction task, where they had to type the word that was presented. The authors found that people with dyslexia had significantly lower accuracy on words presented in the LVF compared to normal controls. This means that people with dyslexia were less accurate at processing words in the LVF than people without dyslexia. Because of the impaired processing of words in the LVF, the RVF advantage is expected to be larger for people with dyslexia than in the normal population, due to an enlarged difference between the accuracy of words in the LVF and the RVF. This was also observed by Henderson et al. (2007) and Bradshaw et al. (2020).

It is still unclear whether people with dyslexia also show a RBA in word processing. Henderson et al. (2007) found that the dyslectic group did not perform better on the typing task when a word was presented in both visual fields as compared to when a word was presented in only the RVF. The RBA was completely absent in the participants with dyslexia. The control group of Henderson et al. (2007) did show a bilateral advantage. Yet, Bradshaw et al. (2020) did find a RBA in people with dyslexia. In their study, the participants with dyslexia did perform with higher accuracy on words that were bilaterally presented compared to words that were only presented in the RVF. In fact, the RBA of the dyslexia groups was not significantly different from the RBA observed in the control group.

The prestation of people with dyslexia on VHF tasks compared to control participants can be explained by the interhemispheric transfer deficit theory (Badzakova-Trajkov et al., 2005; Orton, 1927). This theory proposes that the transfer of information through the corpus callosum is impaired in people with dyslexia, resulting in difficulties in the processing of verbal stimuli. Impaired transfer can explain the difficulties with processing words in the LVF reported by Henderson et al. (2007) and Bradshaw et al. (2020). As stimuli from the LVF are initially projected to the right hemisphere and the transfer between the two hemispheres is impaired, it would take longer for the information in the right hemisphere to travel to the left hemisphere to be processed.

Impaired transfer should also mean a weaker RBA, as it takes information from the LVF longer to reach the left hemisphere. This is indeed what Henderson et al. (2007) found, as they did not find the RBA effect in word processing in people with dyslexia. Yet Bradshaw et al. (2020) observed that people with dyslexia had a RBA that was equally large as the one observed in the control group, and thereby did not replicate the results of Henderson et al. (2007) in favor of the decreased RBA in dyslexia. However, the findings of Bradshaw et al., (2020) are still reconcilable with the interhemispheric transfer deficit theory. Their results can be explained by the possibility that the poorly transferred information of the LVF might still facilitate processing in the left hemisphere to a certain degree, according to the authors. They argue that information of poorer quality is still being transferred from the LVF to the left hemisphere, contributing to word processing. This aligns with the observation that partial cues in the LVF still facilitated the processing of stimuli in the RVF, as mentioned before (Henderson et al., 2007). The degenerated information from the LVF in people with dyslexia could serve as partial cues, facilitating the processing of words in the RVF.

The results of Henderson et al. (2007) and Bradshaw et al. (2020) point to impaired interhemispheric transfer as a possible contributing factor to dyslexia. There is also converging neuroanatomical evidence for this hypothesis: MRI studies have shown structural abnormalities in the corpus callosi of people with dyslexia. Even though the results on the anatomical differences of the corpus callosum have been inconsistent regarding which parts of the corpus callosum are affected (Paul, 2010), differences with control participants were especially observed in the posterior parts of the corpus callosum (Robichon & Habib, 1998; Duara et al., 1991). These are the sections that connect the left and right visual cortex with each other. An additional indication for this hypothesis regarding the corpus callosum in dyslexia comes from similarities between the symptoms of patients with agenesis of the corpus callosum and the symptoms of dyslexia. Agenesis of the corpus callosum is a defect where parts of the corpus callosum are missing (Schell-Apacik et al., 2008). Both groups have problems with phonological priming (Banich & Brown, 2000). This indicates a possible link between impairment of the corpus callosum and phonological processing impairment observed in dyslexia. However, there is no research yet that directly linked structural differences in the corpus callosum of people with dyslexia with impairments in interhemispheric transfer.

As discussed, Henderson et al. (2007) and Bradshaw et al. (2020) have provided substantial behavioral evidence for the interhemispheric transfer deficit theory in dyslexia using the visual half-field task. However, there was one significant limitation to their studies: they only measured accuracy. This is odd, as you would expect that the interhemispheric transfer deficit theory involves matters of processing speed and reaction times. A logical consequence of impaired transfer should be longer processing times (Daini et al., 2018). Slower processing could explain the larger RVF advantage and the weaker RBA in people with dyslexia. However, their VHF task, for which the participants had to type the word which was presented, did not allow for reaction times to be registered.

The current study used a similar VHF paradigm as Henderson et al. (2007) and Bradshaw et al. (2020) used, but with a lexical decision task instead of the typing task. A lexical decision task requires participants to decide whether a presented string of letters forms an existing word in a certain language, in this case Dutch. This task allowed us to measure reaction times on top of accuracy. In line with the previous studies, it is expected that people will perform worse when words are presented in the LVF alone, compared to when words are presented in the RVF alone, resulting in a RVF advantage. For people with dyslexia, who are expected to have an even more decreased performance to words in the LVF, this difference is even larger. This has been observed in lower accuracy rates for words in the LVF. In this study, the aim is to replicate these results using reaction times and accuracy to a lexical decision task. According to the interhemispheric transfer deficit hypothesis, it is expected that the difference in reaction times and accuracy between words presented in the RVF and words presented in the LVF is larger for people with dyslexia than for control participants, resulting in a larger RVF advantage in the dyslexia group.

On top of that, a reduced RBA based on reaction times and accuracy to the lexical decision task is also expected. A deficit in interhemispheric transfer in people with dyslexia would mean that information from the LVF would reach the left hemisphere slower than it would in control participants. The word processing in the left hemisphere would be enhanced at a slower rate with the information in the LVF, and thereby it is expected that the reaction times and accuracy of people with dyslexia would be ‘boosted’ less by bilateral presentation, compared to the reaction times and accuracy scores of control participants. In short, this would mean that the RBA on reaction times and accuracy should be reduced in people with dyslexia.

Additionally, measures of reading and spelling efficiency that are validated in distinguishing people with dyslexia from those who do not have dyslexia (Tops et al., 2012) were also included. These scores did not only serve as a validation that the participants with dyslexia had impaired language abilities as compared to the control group, but were also used for a correlation analysis between the VHF task scores and the language abilities of the participants with dyslexia. If a slower interhemispheric transfer is related to dyslexia, it would be expected that delayed transfer is also related to the severity of the symptoms of dyslexia. As mentioned before, a deficit in interhemispheric transfer can be observed in lower accuracy and longer reaction times to words in the LVF, resulting in an increased RVF advantage. Thereby, it was hypothesized that the size of the RVF advantage based on both accuracy and reaction times would correlate with lower scores on these reading and spelling tests. Delayed interhemispheric transfer can also be observed in a reduced RBA based on accuracy and reaction times. Therefore a second hypothesis regarding a correlation with the language tests, stated that a reduced RBA, based on both accuracy and reaction times, would correlate with lower scores on the reading and spelling tests.

## Method

### Participants

For this study, right-handed bachelor psychology students from Ghent University, who could participate for credit, were recruited. To expand the sample, right-handed participants aged 18 to 40 were also recruited opportunistically through social media and word-to-word publicity. Both people with dyslexia and a control group were recruited. The control group was included as a reference for neurotypical performance and was matched as good as possible to the dyslexia group based on gender, age, and years of education. All participants had Dutch as a first language and had normal or corrected to normal vision. Because handedness is related to hemispheric language dominance in the sense that there is an increased prevalence of atypical right hemispheric language dominance in left-handers (Knecht, 2000), only right-handed participants were recruited. The number of participants was based on the power analysis of Bradshaw et al. (2020), who recommended at least 30 participants per group based on the data of Henderson et al. (2007). At the end of data collection, the sample included 90 participants in total.

The dyslexia group consisted of 45 participants (17 males and 28 females, mean age= 22.31, standard deviation (SD) age= 5.13) who all had received a clinical diagnosis of dyslexia, or who had received a special status at Ghent University due to dyslexia. The participants had a mean duration of education of 13.44 years (SD= 1.91).

The control group also consisted of 45 participants and was perfectly matched by gender. The mean age of this sample was 21.78 years (SD = 5.04) and the mean duration of education was 13.62 years (SD= 1.97). The two groups did not significantly differ in age, $t(87.97) = 0.50$, $p= .62$, nor in duration of education, $t(87.92) = -0.43$, $p= .67$.

**Materials**

***The Ten-Item Edinburgh Handedness Inventory***

As handedness is connected to hemispheric lateralization (Knecht, 2000), the ten-item Edinburgh Handedness Inventory (EHI; Oldfield, 1971) was used to verify all participants were primarily right-handed. The EHI not only assesses handedness based on your preferred hand to write with, but also takes into account other daily actions like using scissors, brushing your teeth, throwing, and so on. It thereby gives a more holistic measure of handedness. The EHI is recommended as a screening tool for laterality (Oldfield, 1971) and is one of the most frequently used methods to measure handedness (Fazio et al., 2011). Participants were asked to indicate whether they prefer to use their right hand, their left hand, or are indifferent to which hand they use for a series of 10 everyday activities. Items where participants indicated a preference for the right hand were scored with 1, items where participants preferred the left hand were scored with 0, and items for which participants were indifferent were scored with 0.5. Total scores can range from 10, strongly right-handed, to 0, strongly left-handed.

***Visual Half-field Task***

The visual half-field (VHF) task was designed following the guidelines of Hunter and Brysbaert (2008), who studied which parameters of the VHF task are important to determine cerebral language dominance. The VHF task existed of words and non-words presented in the left visual field, the right visual field, or presented in both visual fields. A fixation cross was presented in the center of the screen. When a stimulus was only presented in one visual field, a placeholder was shown on the other side, in the form of 'XXXXX', for a balanced visual presentation. A stimulus would appear after 500ms and would be visible for 200ms, after which a mask ('#####') would take the place of the stimuli and would stay visible for 200ms. This was included to avoid an afterglow and to restrict a visual memory of the words, as recommended by Hunter and Brysbaert (2008). The participants had as much time as needed to give their answers, but they were instructed to respond as correctly and as fast as possible. The next trial started after a response was recorded. The participants were asked to focus on a fixation cross in the middle of the screen during the whole trial, to make sure their attention stayed on the middle of the screen and to avoid eye movements towards the stimuli. Figure 2 provides a visual representation of a trial.

The stimuli consisted of 80 five-letter words and 80 five-letter non-words, selected from the Dutch Lexicon Project 2 (Brysbaert et al., 2016) and the Dutch Lexicon Project (Keuleers et al., 2010) respectively. For the word-items, only nouns with an accuracy rate of 100% were selected, as determined by Brysbaert et al. (2016), who had 81 participants perform a lexical decision task on the words. The non-words all had an accuracy-rate from 95% to 96%, based on the lexical decision data of 39 participants collected by Keuleers et al. (2010). The stimuli were all 2.8 cm long and appeared 1.5 cm from the fixation cross. When participants focused on the fixation cross, the visual angle was about 1.4 degrees to the inner side of the presented words, and about 4 degrees to the outer side if the presented words. Therefor the words were presented in the parafoveal visual field, defined as approximately 4 degrees of visual angle from the fixation point (Sakurai, 2020). The stimuli were presented in black on a grey background, in the font 'Fixedsys', which ensures the words always had the same length. The font size was set to 0.85 cm.

The 160 stimuli were each presented once in the left visual field, once in the right visual field, and once bilaterally, resulting in 480 trials. The trials were presented in a random order. The experiment started with 20 practice items, which were randomly selected from the 480 trials. After the practice trials, the participants were given feedback in the form of a score of 20. If it seemed that the participant did not understand the task, the instructions were repeated. The experiment itself consisted of 4 blocks of 120 trials. The participants could take a self-paced break between the blocks by pressing the spacebar when they wanted to continue with the task. The total time of the experiment differed because the participants worked at their own speed.

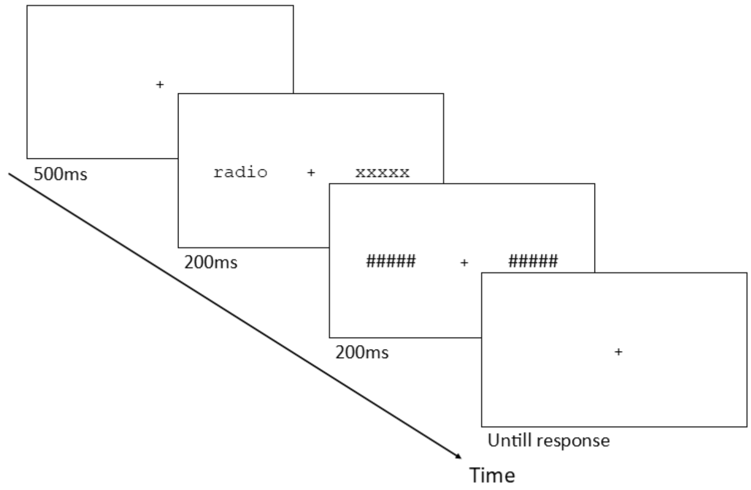
***Reading and Spelling Tests***

A selection of reading and spelling tests were administered to quantify the language skills of the participants. The tests were selected based on a paper by Tops et al. (2012), who studied the identification of students with dyslexia in higher education in Flanders. They determined that Dutch

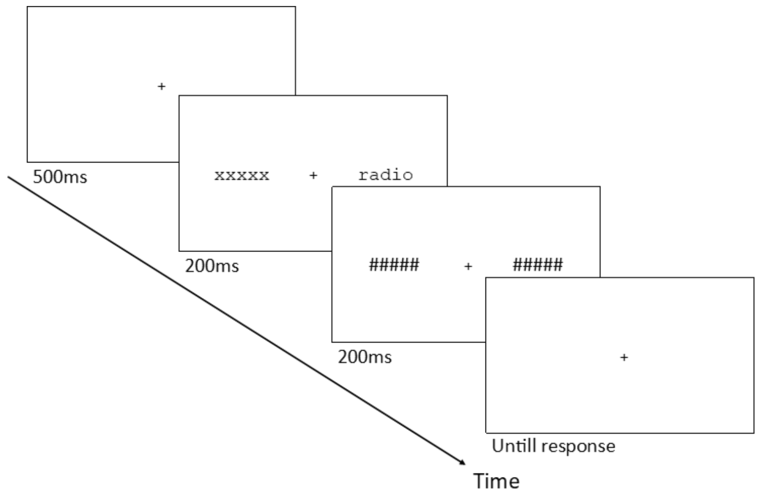
**Figure 2**

*Flowcharts of the three types of VHF-trials*

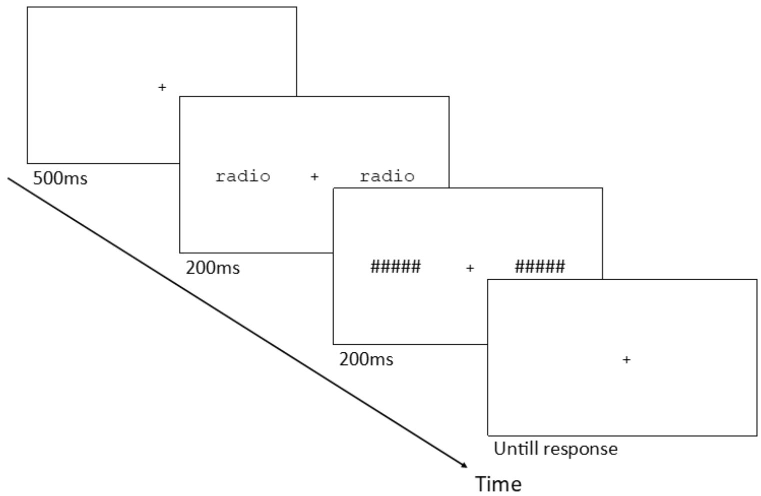
**A**




**B**




**C**




*Note:* Each flowchart visualizes 1 trial, with panel A depicting presentation of a word in the left visual field, panel B depicting presentation in the right visual field, and panel C depicting bilateral presentation. Participants were asked to do a lexical decision task on the presented words and non-words while fixating on the fixation cross in the middle of the screen.

word reading, Dutch word spelling, and phonological awareness were the most important predictors of dyslexia.

**Spelling.** Spelling was assessed by a subtest of an advanced reading and spelling test, the GL&SCHR (Test voor Gevorderd Lezen & Schrijven [Test for Advanced Reading and Writing]; De Pessemier & Andries, 2009). This test exists of 30 Dutch exception words, which were 'read out' by an audio recording at a rate of one word per 2 seconds. Participants had to write down the words with correct spelling. After the recording, they could complete the words they missed and correct possible mistakes. In a separate column on the test paper, the participants then had to indicate per word whether they were 'unsure', 'almost sure', or 'very sure' about the correctness of their spelling. These ratings were then combined with the accuracy of the spelling into a weighted score for word spelling. The weighted score ranges from 0 to 150, with higher scores indicating better performance. The weighted score has an effect size *d* of 2.28 in discriminating between students with dyslexia and those without, which is larger than the effect size of just the number of correctly written words (*d*= 2.05), according to Tops et al. (2012).

**Phonological Awareness.** Another subtest of the GL&SCHR (De Pessemier & Andries, 2009) was used to measure phonological awareness. This subtest was a spoonerism task, where participants had to switch the first letter of two spoken words (e.g. 'Gele Kast' becomes 'Kele Gast'). The words were presented though an audio recording, after which the participants had to orally respond with the two words with reversed first letters. The task consisted of 6 practice items and 20 test items. The total time it took the participants to complete the test items was recorded, as time was the measure recommended by Tops et al. (2012), above accuracy. The time score of the spoonerism task has an effect size *d* of 1.42 in distinguishing between people with dyslexia from those without dyslexia (Tops et al., 2012).

**Reading.** To assess word reading speed, the LEMs or Leestest 1-minuut studenten (Word Reading Test for students; Tops et al., 2019) was used. This test consists of a list of 132 Dutch words, of which the participants had to correctly read aloud as many words as possible in 1 minute. The items are arranged in a rising level of difficulty, as the words become increasingly less frequent. The score for this test ranges from 0 (no words correctly read in 1 minute) to 132 (all words correctly read in 1 minute). This test has a sensitivity of 70 to 85% in detecting people with dyslexia, meaning that 70 to 85% of the lowest scores (according to a 10 to 16% cutoff) belong to participants with dyslexia, based on the data of 200 students of higher education (effect size *d*= 1.97; Tops et al., 2019). This test was chosen instead of the EMT (Eén Minuut Test; Brus & Voeten, 1991), which is often used to measure Dutch reading efficiency. However, the EMT uses outdated words and tends to have a ceiling effect in students of higher education (Tops et al., 2019).

**Procedure**

The participants were tested individually in a quiet room in a session of about one hour. The sessions started with two short questionnaires on demographics and handedness, after which the visual half-field task was administered. The visual half-field task was conducted using Psychopy2 (Peirce et al., 2019) to present the stimuli and record the responses. The participants were positioned 60 cm from a 15-inch PC screen. They were asked to do a lexical decision task on the words and non-words, which would either appear on the left side, on the right side, or on both sides of the screen simultaneously. To answer, the participants had to place their index and middle finger of both hands on marked keys on a free-standing keyboard ('J' and 'F' for the index finger, and 'E' and 'I' for the middle finger). They were instructed to press both index fingers when they saw an existing word, and press both middle fingers if they saw a non-word. Participants always had to use both hands to answer, because when people are asked to answer with either the left or right hand, the congruence between the place of presentation of the stimuli and the hand they answer with can influence accuracy and reaction times (Simon, 1969). The sessions ended with a battery of tests to assess the participants' reading and spelling skills. Students received a credit for their participation, other participants received a monetary compensation.

**Analysis**

Analyses were conducted in R (R Core Team, 2019) and figures were generated with the packages ggplot2 (Wickham, 2016) and yarrr (Phillips, 2017). Only the accuracy scores and reaction times to words were analyzed, as this study focusses on written word comprehension. Before the statistical tests, outliers were removed based on the reaction times. Trials with reaction times shorter than 250ms were omitted, as these were too short to represent a reaction time regarding a lexical decision (Barca & Pezzulo, 2012). Trials with a reaction time 2.5 standard deviation higher than the participant's mean reaction time were also excluded, as these were considered outliers (Ratcliff, 1993). For further analyses on reaction times, only the reaction times of correct responses were included. Accuracy rates were converted into accuracy percentage scores.

In a group comparison, two hypotheses concerning accuracy and reaction times were considered: (1) the RVF advantage (measured as the difference between the RVF and the LVF) is larger in the dyslexia group than in the control group based on both accuracy and reaction times, and (2) the redundant bilateral advantage (RBA) for people with dyslexia is reduced for accuracy and reaction times compared to the RBA of the control group. For the first hypothesis, the difference between reaction times to words in the RVF and reaction times to words in the LVF were calculated per participant. The difference in accuracy was calculated in the same way.

For the second hypothesis, the RBA had to be estimated for each participant. The presence of the RBA is reflected by faster reaction times to bilateral presentation compared to reaction times to the preferred visual half-field. It is possible that some people actually have a preference for and perform better to items in LVF instead of the RVF. This can be determined with the difference scores described above. Participants with a positive difference in reaction times, meaning that the reaction times to words in LVF are faster, show a LVF advantage instead of a RVF advantage. This can also be observed in a negative difference in accuracy, meaning that they perform with higher accuracy for words in the LVF. Based on the negative or positive valence of the differences, it was determined whether the participants have a preference for the RVF or the LVF. To calculate the RBA based on reaction times, the response times to trials in the preferred visual field were subtracted from the response times of the bilaterally presented trials for each participant. The RBA of accuracy was calculated in the same way as for the reaction times. A RBA in accuracy is reflected by higher accuracy scores for trials with bilateral presentation compared to trials of unilateral presentation in the preferred visual field. Because both hypotheses are very specific regarding the direction of the difference between the control group and the dyslexia group, one-sided independent sample t-tests were used to compare the calculated difference scores between the groups.

To analyze the relationship between impaired interhemispheric transfer of people with dyslexia and their scores on the reading and spelling tests, partial correlations were calculated between the scores on the language tests and the differences in reaction times and accuracy between the RVF and the LVF in the dyslexia group, taking into account the duration of education of the participants and their gender. These variables were considered because duration of education is related to higher language abilities (Conti-Ramsden et al., 2018), and because women score systematically higher on spelling and reading tests (Reilly, 2020). Also the RBA based on the reaction times and accuracy was tested for correlation with the performance on the language tests in the dyslexia group, controlling for duration of education and gender. For all statistical tests, an alpha level of 0.05 was used. Multiple comparisons were accounted for by Bonferroni corrected p-values. Normality assumptions were checked visually with the car package in R (Fox & Weisberg, 2019).

## Results

### Handedness and Language Abilities

As measured with the EHI, both the participants of the dyslexia group and the control group were all strongly righthanded ($M_{dys}$= 9.68, $SD_{dys}$= 0.53; $M_{con}$= 9.71, $SD_{con}$= 0.57). The groups did not significantly differ based on their EHI scores, $t(87.66)$= -0.286, $p$ = 0.78. Mean scores on the different reading and spelling tests are displayed in Table 1. Participants of the control group scored significantly better on spelling, $t(87.73)$ = 9.48, $p$ < .001, the spoonerism task on phonological awareness, $t(58.26)$ = -5.78, $p$ < .001, and the LEMs reading test $t(87.20)$ = 9.64, $p$ < .001. Based on these tests, the dyslexia group had significantly reduced language abilities as compared to the control group.

**Table 1**

*Mean (SD) of language test scores*

| Language Test | Control | Dyslexia |
|---|---|---|
| Spelling GL&SCHR | 121 (12) | 96 (13) |
| Phonological Awareness (spoonerism score) | 57 (19) | 101 (47) |
| LEMs (words/min) | 106 (17) | 74 (15) |

*Notes:* SD = standard deviation, GL&SCHR= Test voor Gevorderd Lezen & Schrijven (De Pessemier & Andries, 2009), LEMs = Leestest 1-minuut studenten (Tops et al., 2019)

**Right Visual Field Advantage**

Mean accuracy percentages and reaction times per visual half-field condition are summarized for each group in Table 2 and Figure 4. To confirm a RVF advantage in accuracy was observed in the current data, it was tested whether the accuracy scores to the words presented in the RVF were higher than those of the LVF, based on the data of the control group. A one-sided paired t-test validated that accuracy was higher for the RVF trials compared to the LVF trials, $t(44) = 3.92$, $p < .001$. The same test was used to verify whether also a right visual field advantage based on the reaction times was observed, based on the data of the control group. This confirmed that reaction times of the RVF condition were faster than those of the LVF condition, $t(44) = -2.28$, $p = .027$. Thereby a RVF advantage was observed in the control group based on accuracy and reaction times.

Our first hypothesis stated that the RVF advantage, as measured by the difference in accuracy and reaction times between the RVF and the LVF, would be larger in the dyslexia group. However, a one-sided independent sample t-test indicated no significant difference in the calculated RVF-LVF differences between the groups based on accuracy, $t(86.68) = 0.21$, $p = .83$, nor based on reaction times, $t(57.02) = -1.75$, $p = .086$. The group comparisons on the RVF-LVF difference scores are visually displayed in the pirate plots in Figure 5.

**Table 2**

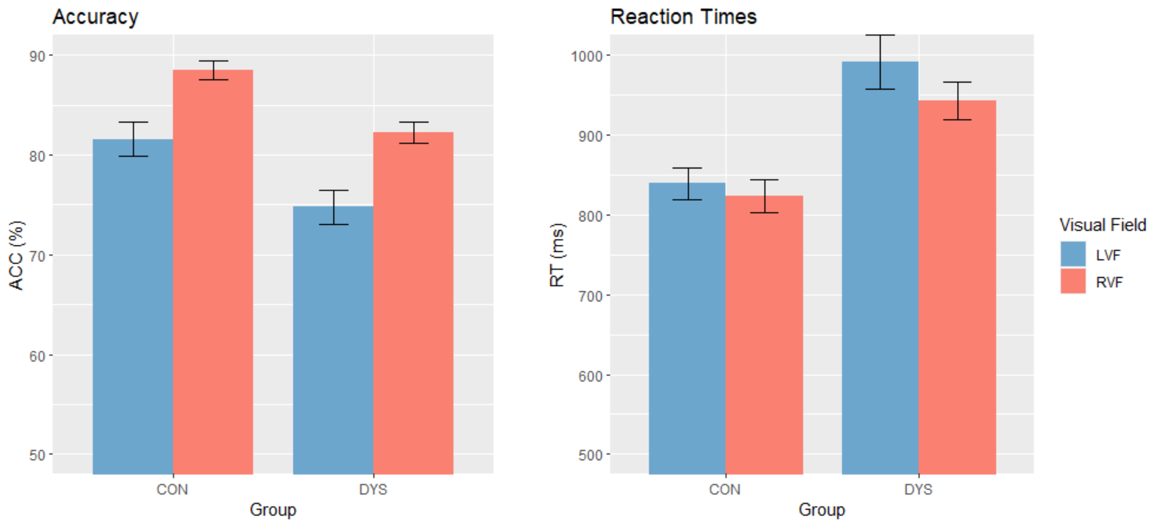
*Mean Scores (and SD) on the VHF Task per Group*

| Measure | Group | LVF | RVF | BVF | RVF-LVF difference | RBA |
|---|---|---|---|---|---|---|
| *Accuracy* | Control | 81.6% (11.7) | 88.5% (6.1) | 94.1% (3.9) | 6.9 (11.8) | 4.2 (4.8) |
| | Dyslexia | 74.8% (11.2) | 82.2% (7.3) | 90.7% (5.5) | 7.4 (13.3) | 6.4 (5.4) |
| *RT (ms)* | Control | 839 (134) | 824 (141) | 787 (128) | 16 (46) | -27 (27) |
| | Dyslexia | 991 (225) | 943 (159) | 904 (165) | 48 (117) | -22 (59) |

*Notes:* SD= standard deviation, VHF= visual half-field, LVF= left visual field, RVF= right visual field, BVF= bilateral visual field, RBA= redundant bilateral advantage, RT= reaction time

**Figure 4**

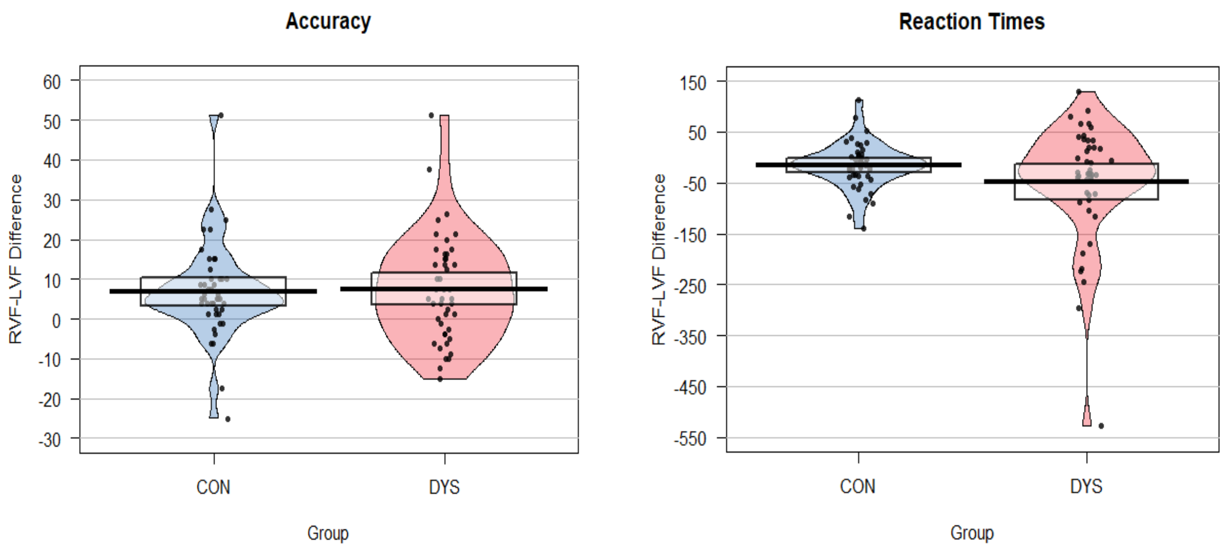
*Bar Plots of the Left and Right Visual Field per Group*




*Notes:* Bar plots of the mean accuracy (in %) and mean reaction times (in ms) per visual half-field condition per group, with standard error in black. Bars start at 50% accuracy and 500ms reaction time. ACC= accuracy, RT= reaction time, RVF= right visual field, LVF= left visual field, CON= control group, DYS= dyslexia group

**Figure 5**

*Pirate Plots of RVF Advantage per Group*




*Notes:* RVF-LVF difference of both accuracy and reaction times, visualized in pirate plots displaying the mean and individual data points of the two groups. The shaded boxes represent the 95% confidence intervals. RVF= right visual field, LVF= left visual field, CON= control group, DYS= dyslexia group

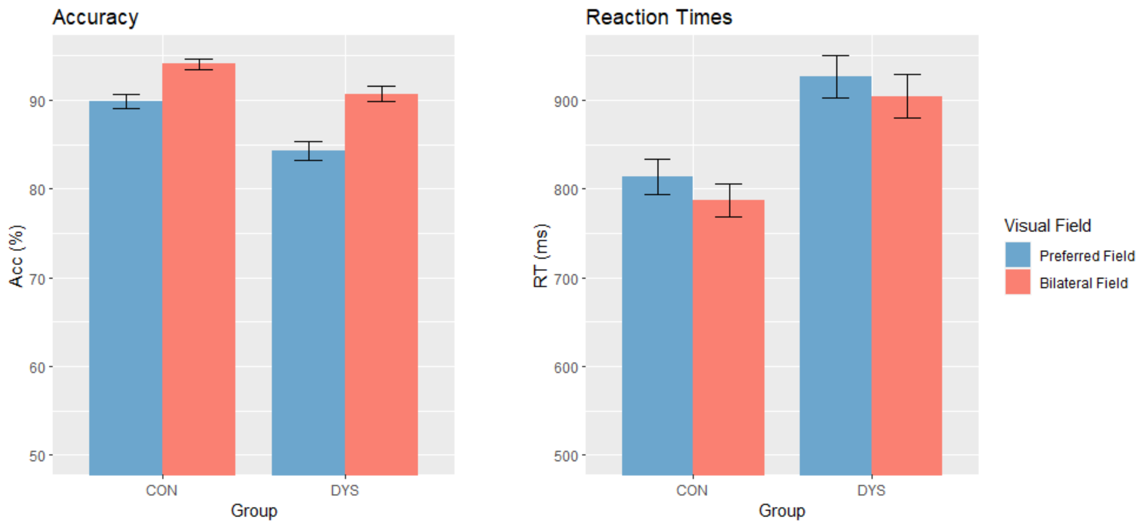
Because these results do not stroke with the results of the previous studies (Henderson et al., 2007; Bradshaw et al., 2020), post hoc analyses were done to further explore the current findings. Bradshaw et al. (2020) and Henderson et al. (2007) argued that the observed RVF advantage could be explained by reduced accuracy to words in the LVF, but no reduced accuracy to words in the RVF in their dyslexia groups. Therefore, additional analyses were done to compare the performances regarding the LVF and the RVF between the groups. This was done by independent t-tests, which compared the accuracy and the reaction times to the LVF and the RVF separately between the groups. Accuracy was significantly lower in the dyslexia group compared to the control group for both trials of the LVF, $t(87.88) = -2.82$, $p = .024$, and the RVF, $t(85.62) = -4.40$, $p < .001$. Reaction times were significantly longer in the dyslexia group than in the control group regarding both the LVF, $t(71.89) = 3.90$, $p < .001$, and the RVF, $t(86.86) = 3.77$, $p = .001$.

**Redundant Bilateral Advantage**

RBA scores are summarized for each group in Table 2 and mean accuracy and reaction times of the bilateral and the preferred visual field are displayed in Figure 6. To confirm a significant RBA was observed based on accuracy with our task, a one-sample one-sided t-test was used to test if accuracy in the bilateral visual field condition was higher than accuracy to trials of the preferred unilateral visual field in the control group. This test validated that higher scores were observed in the bilateral condition, $t(44) = 5.80$, $p < .001$. The same method was used to test whether also a RBA

**Figure 6**

*Bar Plots of Preferred and Bilateral Visual Field per Group*



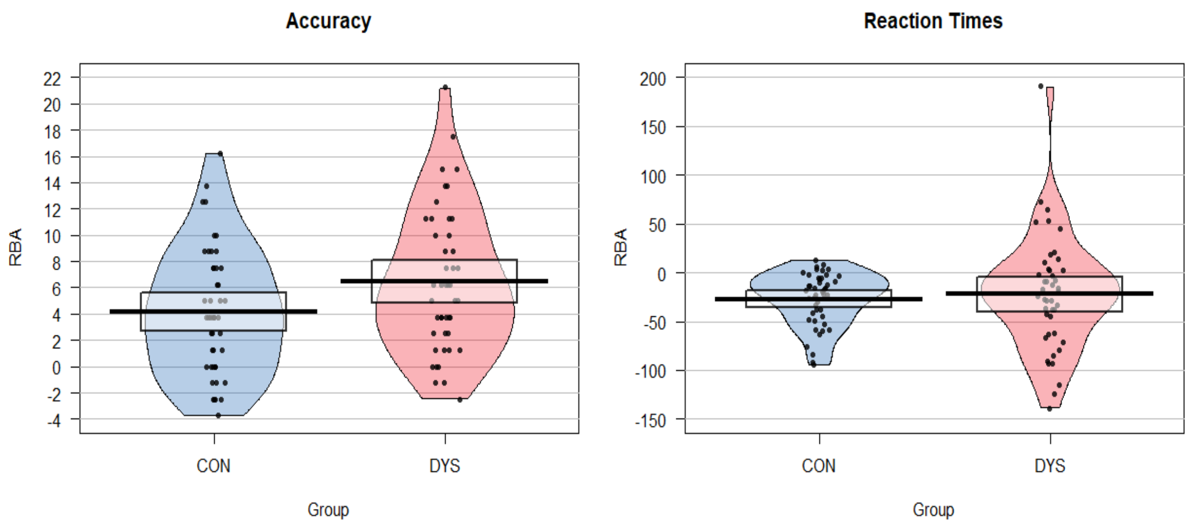

*Notes:* Bar plots of the mean accuracy (in %) and mean reaction times (in ms) for the preferred visual field and the bilateral visual field per group, with standard error in black. Bars start at 50% accuracy and 500ms reaction time. ACC= accuracy, RT= reaction time, CON= control group, DYS= dyslexia group based on reaction times was observed in the control group. This verified that the reaction times to the trials of the bilateral visual field were shorter than those of the preferred unilateral visual field, $t(44) = -6.60$, $p < .001$. Based on both accuracy and reaction times, a significant RBA was observed in the control group.

Based on the second hypothesis, it was expected that the RBA would be reduced in the dyslexia group. However, a one-sided independent t-test indicated that the RBA observed in the dyslexia group was not smaller than the RBA observed in the control group, both based on accuracy scores, $t(86.95) = 2.08$, $p = 1$; and on reaction times, $t(62.45) = 0.51$, $p = .61$. The RBA scores per group are visually displayed in Figure 7.

Eight control participants and fourteen participants with dyslexia did not show a typical preference for the RVF based on their accuracy scores, meaning that they either had a preference for LVF trials compared to RVF trials, or their performance did not differ between the two visual half-fields. Based on reaction times, thirteen control participants and fifteen participants with dyslexia did not demonstrate a typical RVF preference, and instead showed a preference for the LVF or did not perform differently regarding both visual fields. The current study took into account the preferred visual field to calculate the RBA, while Henderson et al. (2007) and Bradshaw et al. (2020) used the RVF as a reference for the RBA for all participants. Because a different method of calculation of the

**Figure 7**

*Pirate Plots of the RBA per Group*




*Notes:* The RBA based on accuracy and reaction times, visualized in pirate plots displaying the mean and individual data points of the two groups. The shaded boxes represent the 95% confidence intervals. RBA= redundant bilateral advantage, CON= control group, DYS= dyslexia group

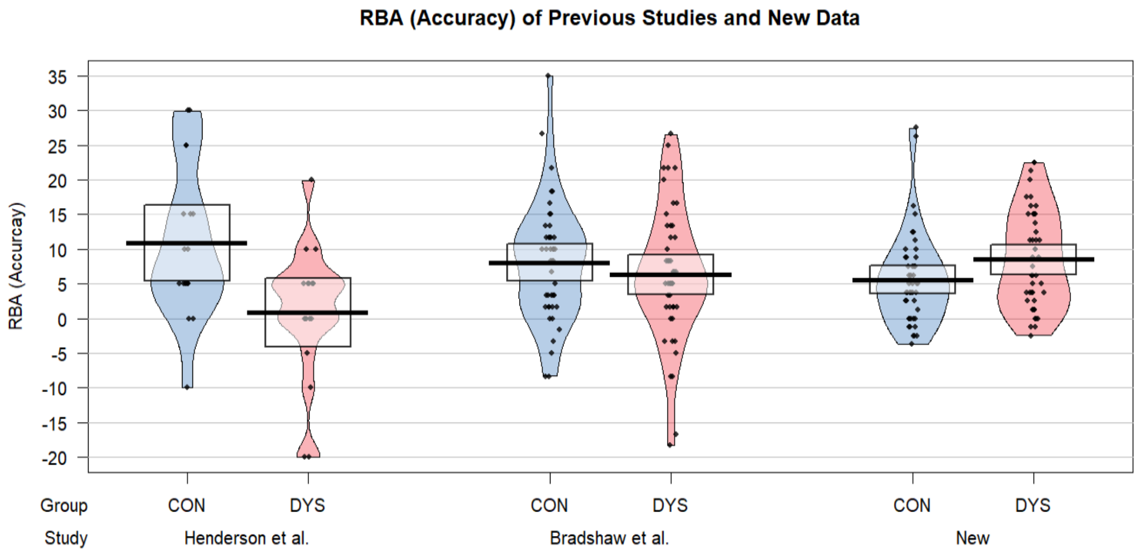
RBA than in the previous studies was used, a post hoc exploratory analysis was carried out to verify whether the current results were not affected by this. This was tested by a one-sided independent t-test with the RBA calculated as Henderson et al. (2007) and Bradshaw et al. (2020) did. This did not change the outcome of the tests, as the group difference for the RBA based on accuracy was still non-significant, $t(87.78) = 2.00$, $p = .98$; and so was the group difference for the RBA based on reaction times, $t(66.03) = -0.18$, $p = .57$. A visual comparison between our new data and the data of Henderson et al. (2007) and Bradshaw et al. (2020) is presented in Figure 8.

**Correlation with Reading and Spelling Abilities**

To explore the relation between the RVF advantage in the dyslexia group and their performance on the independent reading and spelling tests, partial correlation analyses were run, taking into account gender and years of education. The correlations were calculated for the RVF advantage based on both accuracy and reaction times. The RVF advantage based on accuracy scores

**Figure 8**

*RBA of Previous Studies Compared to New Data*




*Notes:* Comparison of the RBA based on accuracy of the previous studies of Henderson et al. (2007) and Bradshaw et al. (2020), and the new data of the current study, visualized in pirate plots displaying the mean and individual data points of the two groups. The shaded boxes represent the 95% confidence intervals. Note that the visualization of the data of Henderson et al. (2007) is based on the data of 18 participants per group, as not all data was available. RBA= redundant bilateral advantage, CON= control group, DYS= dyslexia group correlated with none of the scores of the language tests: spelling GL&SCHR, *r*(0.65) = 0.10, *p* = 1; phonological awareness, *r*(-1.45) = 0.06, *p* = .94; LEMs reading test, *r*(-0.25) = -0.13, *p* = 1. Neither did the RVF advantage based on reaction times correlate significantly with the language sores: spelling GL&SCHR, *r*(0.36) = 0.06, *p* = 1; phonological awareness (spoonerisms), *r*(0.42) = -0.22, *p* = 1; LEMs reading test, *r*(-0.81) = -0.04, *p* = 1. A visualization of the results can be found in the Appendices, Figure 1.

Furthermore, partial correlations were also tested between the RBA scores and the independent reading and spelling test scores of the participants with dyslexia, taking into account gender and years of education. The correlation tests were run for the RBA based on both accuracy and reaction times. No significant correlation was found between the RBA based on accuracy and the language abilities: spelling GL&SCHR, *r*(2.36) = 0.35, *p* = .14; phonological awareness, *r*(-2.47) = -0.36, *p* = .11; LEMs reading test, *r*(0.13) = 0.02, *p* = 1. Nor was a significant correlation found between the RBA based on reaction times and the language tests: spelling GL&SCHR, *r*(-0.01) = 0, *p* = 1; phonological awareness, *r*(1.34) = 0.20, *p* = 1; LEMs reading test, *r*(-0,81) = -0.13, *p* = 1. The scatterplots in Figure 2 in the Appendices provide a visualization of the results.

## Discussion

The current study focusses on the interhemispheric transfer deficit theory in dyslexia. According to this theory, dyslexia is related to impaired hemispheric transfer. This can be observed with a visual half-field paradigm (Hellige, 1993), which is a behavioral method to study lateralization by presenting words in the left visual field, the right visual field, or bilaterally. Using this method, it has been demonstrated that participants with dyslexia performed with decreased accuracy to words presented in the LVF compared to a control group, which can be explained by delayed hemispheric transfer in the dyslexia group (Bradshaw et al., 2020; Henderson et al., 2007). This resulted in an increased RVF advantage and a decreased redundant bilateral advantage (RBA) in the participants with dyslexia. However, these results were only based on accuracy scores.

As delayed hemispheric transfer should be reflected by longer processing time, this should also be observable in delayed reaction times to words in the LVF. The aim of the current study was to study the interhemispheric transfer deficit in dyslexia by using a lexical decision task, which allowed for the registration of both accuracy scores and reaction times. Using this task, two hypotheses were tested: (1) the RVF advantage is increased in participants with dyslexia based on their accuracy and reaction times and (2) the RBA measured by accuracy and reaction times is decreased in participants with dyslexia. Additionally, the relation between the intensity of the RVF advantage and the RBA, and the language test scores were also tested in the dyslexia group with partial correlation analyses.

Using a lexical decision task, this study found a RVF advantage in both accuracy and reaction times, based on the data of the control group. Thus, the lexical decision task was a successful task for the observation of the RVF advantage in written word processing. The RVF advantage observed in the dyslexia group was not significantly larger than the RVF advantage observed in the control group, based on both accuracy and reaction time scores. This is inconsistent with the first hypothesis, which predicted that the RVF advantage would be larger in the dyslexia group compared to the control group.

Based on both accuracy and reaction times on the lexical decision task, a RBA was observed with this task, based on the data of the control group. Therefor the lexical decision task was a valid task for the observation of the RBA in written word processing as well. However, the RBA observed in the dyslexia group was not significantly smaller than the RBA observed in the control group. This was the case for both accuracy and reaction time measures. These results do not support the second hypothesis that the RBA would be reduced in the dyslexia group compared to the control group.

The results concerning the RVF advantage based on accuracy are not consistent with the previous results of Henderson et al. (2007) and Bradshaw et al. (2020), who found an increased RVF advantage in their participants with dyslexia, compared to a control group. Based on the results of the current study, the RVF advantage was not increased in the dyslexia group, but equally large as in the control group. This cannot be explained by an insufficient difference in language skills between the groups, as the dyslexia group performed significantly poorer on tests of reading, spelling, and phonological awareness, which are tests that are considered to be valid in discriminating between participants with and without dyslexia (Tops et al., 2012). What does seem to drive these divergent results, is that based on the data of this study, the accuracy and the reaction times of the dyslexia group were surprisingly impaired for both the LVF and the RVF. This differs from the findings of Henderson et al. (2007) and Bradshaw et al. (2020), where performance to the LVF was impaired in the dyslexia group, but performance to trials of the RVF was not affected. The authors suggested that it was the difference in performance to the LVF that explained the increased RVF advantage in the dyslexia group. It is possible that in the current study no increased RVF advantage was observed because performance was reduced for both the LVF and the RVF.

The results regarding the RBA were also inconsistent with the findings of Henderson et al. (2007), which indicated an absence of the RBA in dyslexia. Bradshaw et al. (2020) did find a RBA in the dyslexia group which was not significantly different from the control group. This is more in line with the results of this study. However, based on visual inspection of our data, the RBA seems to be increased in the dyslexia group, especially in accuracy (see Figure 8). This is surprising, as this is not in line with the interhemispheric transfer hypothesis, based on which the RBA should either be absent or decreased in the dyslexia group (Badzakova-Trajkov et al., 2005; Marks & Hellige, 1999). Still, it is not certain the RBA was significantly larger in the dyslexia group, as this was not statistically tested because this was outside the expectations of the hypotheses. Again, these deviating results cannot be explained by insufficient differences in language abilities between the groups, as the participants with dyslexia had significantly lower performance regarding the tests of spelling, phonological awareness, and reading. The current results could rather be explained by the surprisingly decreased performance to words in the RVF. As most participants had a preference for the RVF, and performance of this condition was decreased in the dyslexia group, this could have enlarged the difference between performance to the preferred field and performance to words that were bilaterally presented, resulting in an increased RBA in the dyslexia group.

**Different Task and Methodological Differences**

One major factor that could have influenced the results of the current study is the used task. This study used a lexical decision task rather than the typing task of Bradshaw et al (2020) and Henderson et al. (2007), to make it possible to include reaction times as a measure as well. However, the use of the different task also had other implications. The most notable implication is that the lexical decision task and the typing task do not necessarily entail the same cognitive processes. A lexical decision task requires the evaluation of words and non-words based on lexical information like orthography, phonology, and semantics (Balota & Chumbley, 1984; Plaut, 1997; Ratcliff et al., 2004), whereas the typing task requires the orthographic reproduction of the presented words. So the typing task involves word (re)production, while word production is not necessarily required in the lexical decision task. Vice versa, semantic processing is not necessarily involved in the typing task. Previous research has proven the involvement of semantic processing in lexical decision tasks, especially in choices regarding words (and not non-words; Binder et al., 2003). As the current analyses only included the performance to the words, semantic processing could have played an important part in the current results of the lexical decision task. It is possible that the previous studies found evidence for the interhemispheric transfer deficit theory in dyslexia because it applies to word (re)production, but not to other lexical processes, like semantic processing.

Semantic processing and word reproduction are also related to different areas in the brain, based on fMRI studies. Semantic processing involves more frontal areas, including the left inferior frontal gyrus, the left cingulate cortex, and the left superior frontal region (Cuenod et al., 1995; Demb et al., 1995). Word reproduction, specifically by typing, has been linked to activation in the left superior parietal lobe, the left supramarginal gyrus, and parts of the left premotor cortex (Higashiyama et al., 2015). These areas are located more to the posterior side of the left hemisphere. There is the possibility that an interhemispheric transfer deficit was observed using a word reproduction task, but not by using a lexical decision task, due to a relation with the neuroanatomical differences in the corpus callosum observed in dyslexia. Previous research indicates that especially the posterior part of the corpus callosum is neuroanatomically affected in people with dyslexia (Robichon & Habib, 1998; Duara et al., 1991). This part of the corpus callosum is connected to the area related to the typing task. Maybe an interhemispheric transfer deficit was observed with that task, because that part of the corpus callosum, which stands in for the transfer between the hemispheres, is affected by dyslexia. On the other hand, there is no indication of neuroanatomical differences in dyslexia in the frontal part of the corpus callosum (Paul, 2010). This could explain why there was no interhemispheric transfer deficit observed in the dyslexia group using a lexical decision task, as this task might have relied more on the frontal areas of the left hemisphere (Cuenod et al., 1995; Demb et al., 1995), which are connected to the frontal part of the corpus callosum.

Besides the use of the lexical decision task, there were also some other methodological differences compared to the previous studies (Bradshaw et al., 2020; Henderson et al., 2007). The stimulus presentation of the current study was 200ms long, whereas the previous studies used a shorter stimulus presentation of 60ms. A stimulus presentation time of 200ms is conform with the results of Hunter & Brysbaert (2008), who recommend caution with using very short presentation times, as the quality of a stimulus presented in the parafoveal field is already suboptimal (Anstis, 1974). However, the use of a longer presentation time might enable participants to make eye movements away from the fixation cross. Participants often struggle with fixating on a central point (Jordan et al., 1998; van der Haegen et al., 2011). Although a study by Walker and McSorley (2006) reported that participants typically need more than 200ms to make an eye movement towards a target, it is possible that participants made eye movements away from the fixation cross before the onset of a trial. Thereby the stimuli might not be presented in the relevant half-field, which is essential for the visual half-field paradigm, which relies on the contralateral projection of the visual field. By not being able to fully control in which visual field the stimuli were presented, it cannot be concluded with certainty that the words were initially projected on the contralateral hemisphere. However, other studies have reported that deviations from central fixation by participants do not impact the observation of VHF effects like the RVF advantage on a group level (Jordan et al., 1998; van der Haegen et al., 2011). Future studies could investigate this further by monitoring fixation, for example with the use of eye tracking.

Another difference from the previous studies is the calculation method of the RBA. Both Henderson et al. (2007) and Bradshaw et al. (2020) used the RVF as a reference to calculate the RBA. However, not every participant had a preference for the RVF over the LVF, as some participants scored with higher accuracy to the LVF. Thereby, using the RVF to calculate the RBA could overestimate the size of the individual RBA. For this reason, the current study first determined the preferred visual field based on accuracy and reaction times, before calculating the RBA based on the difference in performance between the preferred field and the bilateral field. This method ensured that the RBA would not be overestimated. Nonetheless, the use of this other method cannot explain the deviating results, as, when running the same test with the RBA calculated the same way as Henderson et al. (2007) and Bradshaw et al. (2020) did, the results did not change.

**Correlation with Language Abilities**

If impaired interhemispheric transfer is related to dyslexia, it would also be expected that delayed transfer is related to the severity of the symptoms of dyslexia. However, partial correlation analysis revealed no significant relations between the reading, spelling, and phonological awareness scores and the RVF advantage or with the RBA in the dyslexia group. It must be noted that low group variability was observed in the VHF task data. This could have affected the results of the correlation analysis, as a decrease in variability reduces the correlation that a variable has with other variables (Eledum, 2017). Also, the VHF method is not considered powerful enough to determine language lateralization on the individual level (Hunter & Brysbaert, 2008), as there is a high level of individual variability. This also adds to a less reliable correlation analysis. On group level, the VHF method still provides a reliable measure of language lateralization (Brederoo et al., 2019). Taking these limitations together, the results of the correlation analyses should be interpreted with caution.

**Implications of the Current Study**

The current study uncovered several theoretical implications on the processing of written words in dyslexia and raises a few intriguing questions regarding the interhemispheric transfer deficit in dyslexia. Participants with dyslexia performed overall poorer on the lexical decision task than the control participants, to both words presented in the LVF and the RVF. This is in line with previous research, which demonstrated that participants with dyslexia perform with decreased accuracy and increased reaction times to lexical decision tasks (Martens & De Jong, 2006). This provides insight on the orthographic, phonological, and semantic processing in dyslexia, as these are cognitive processes related to lexical decision tasks (Balota & Chumbley, 1984; Plaut, 1997; Ratcliff et al., 2004). The current results indicate that at least some of these processes are impaired in dyslexia. And, as a RVF advantage was observed in both groups, this study also provided evidence that these processes are lateralized in the left hemisphere in both control participants and participants with dyslexia. This is consistent with previous imaging studies, which linked lexical processing on the word level primarily to the left hemisphere (Gernsbacher & Kaschak, 2003).

Contrary to the hypotheses, the reduced performance in the dyslexia group could not be explained by impaired transfer. This finding provides new insights regarding the interhemispheric transfer deficit theory in dyslexia. Previous research (Bradshaw et al., 2020; Henderson et al., 2007) suggested that written word comprehension in dyslexia is affected by impaired interhemispheric transfer, whereas the current results demonstrate that this hypothesis does not apply to all aspects of written word comprehension. Future research should focus on identifying which processes are affected by impaired hemispheric transfer in dyslexia.

The current study also uncovered a possible link between neuroanatomical differences in the corpus callosum of people with dyslexia and impaired hemispheric transfer. Previous research in the healthy population suggests that semantic processing is important for lexical decisions regarding words (Binder et al., 2003). As the current study only took into account responses to words, it can be assumed that the recorded response times and accuracy scores are related to the semantic processing of words. This could also explain why no interhemispheric transfer deficit was observed. Semantic processing is related to more frontal areas of the brain (Cuenod et al., 1995; Demb et al., 1995), and the frontal part of the corpus callosum, which is connected to those areas, does not seem to be affected by dyslexia (Paul, 2010). Because the corpus callosum stands in for the communication between the hemispheres (Steinmann et al., 2017), it can be assumed that interhemispheric transfer impairments are related to impairments in the corpus callosum. In dyslexia, structural differences in the posterior part of the corpus callosum have been observed (Robichon & Habib, 1998; Duara et al., 1991). This could explain why impaired transfer has been observed in processes regarding more posterior areas of the brain, like word reproduction (Bradshaw et al., 2020; Henderson et al., 2007), but not in the current task, which possibly involved more frontal semantic processing. However, this is only a proposition, as there are no studies that have analyzed interhemispheric transfer in dyslexia on the individual levels of word processing, like semantic, phonologic, or orthographic processing. Future research should analyze the different processing levels separately, to examine to which specific processes the interhemispheric transfer deficit theory is applicable, and relate this to the affected areas of the corpus callosum in people with dyslexia.

The hypothesis that the lexical decision task reflected semantic processing would also mean that, based on the current results, semantic processing is impaired in dyslexia. There is limited research on semantic processing in dyslexia, but there is some indication of altered semantic processing in people with dyslexia based on functional activation (Backes et al., 2002). However, lexical decision tasks entail not only semantic processing but also orthographic and phonological processes (Balota & Chumbley, 1984; Plaut, 1997; Ratcliff et al., 2004). With the current paradigm, it is not possible to distinguish between these processes. Therefore it cannot be concluded with certainty that semantic processing was impaired in dyslexia based on the current results. Even though Binder et al. (2003) found indication that lexical decisions regarding words mainly rely on semantic processing, this might not be the same case in people with dyslexia. Araújo et al. (2014) have argued that participants with dyslexia use different techniques to solve lexical decision tasks as control participants, and therefore it is possible that they do not rely on semantic processing the same as the normal population. Accordingly, this interpretation of semantic processing in dyslexia should be treated with caution. More extensive research is needed to explore and understand how dyslexia affects semantic processing.

**Limitations and Future Research**

There are a few limitations to the current study that could be addressed in future research. One important limitation is that the used paradigm did not allow for the observation of written word comprehension on the different processing levels. Even though there was indication of involvement of semantic processes, no substantial conclusions could be drawn about this. If, as the current study suggests, the interhemispheric transfer deficit theory in dyslexia is only applicable to certain types of written word processing, future research should try to further identify these processes.

The design of the lexical decision task also resulted in some other limitations. Firstly, the task was too easy based on the accuracy scores. Accuracy ranged from 75 to 90% in the dyslexia group and from 80 to 95% in the control group. Ceiling effects like this can result in underestimated variability (Nikolopoulou, 2023). This means that the variability in performance to the visual half-field task may be higher in the larger population than the variability that was observed in the current study. Thereby the observed differences between the control group and the dyslexia group could have been underestimated, as lower variability can lead to the observation of smaller differences between groups (Šimkovic & Träuble, 2019). Further research should try to implement the same lexical decision task with harder items, to study how this influences variance and the observed group differences.

Secondly, another limitation is that eye movements away from the fixation cross were not controlled for. Given the longer stimulus presentation time, it cannot be guaranteed that the stimuli were always presented in the relevant visual half-field if participants struggled to stay fixated. An interesting aspect for future research would be to control for eye movements, for example with eye tracking, and test the relation between stimulus presentation time and eye movements away from the fixation cross and performance on a VHF task. Longer stimulus presentation times could have led to a higher possibility of eye movements toward the relevant stimulus, but shorter presentation times could have affected the performance due to decreased quality of the stimulus. It would be relevant for future research to look into this trade-off.

It should also be noted that there are some limitations commonly associated with the use of a VHF paradigm. There generally is a high level of individual variability in performance to a VHF task, making this paradigm unreliable on an individual level (Hunter & Brysbaert, 2007). To determine individual language lateralization, fMRI would be a more reliable measure (Van der Haegen at el., 2011). However, the VHF method is still reliable to use on a group level (Brederoo et al., 2019). Another general criticism of VHF tasks is the use of difference scores. Difference scores are often associated with higher unreliability (Thomas & Zumbo, 2011). Yet, for the purpose of this study, the use of difference scores was relevant for the measurement of the RVF advantage and the RBA.

**Conclusion**

Despite these limitations, this study provides new insights into the interhemispheric transfer deficit theory in dyslexia. Participants with dyslexia performed with lower accuracy and increased reaction times on the lexical decision task, and there was a clear lateralization observed in both the dyslexia group and the control group. There was no indication of impaired interhemispheric transfer in dyslexia based on the performance on the lexical decision task. This has implications for the interhemispheric transfer deficit theory in dyslexia, which states that difficulties with written word processing in dyslexia are due to impaired interhemispheric transfer. The current results, in combination with previous research (Bradshaw et al., 2020; Henderson et al., 2007), suggest that impaired interhemispheric transfer applies to some processes, like word reproduction, but not to others, like the processes involved in lexical decisions. There is a need for further research to identify in which processes of word comprehension and production the interhemispheric transfer deficit in dyslexia is observable. Additionally, the relation between the location of the neuroanatomical differences in the corpus callosum and the cognitive processes affected by impaired interhemispheric transfer in dyslexia should also be considered in future research.

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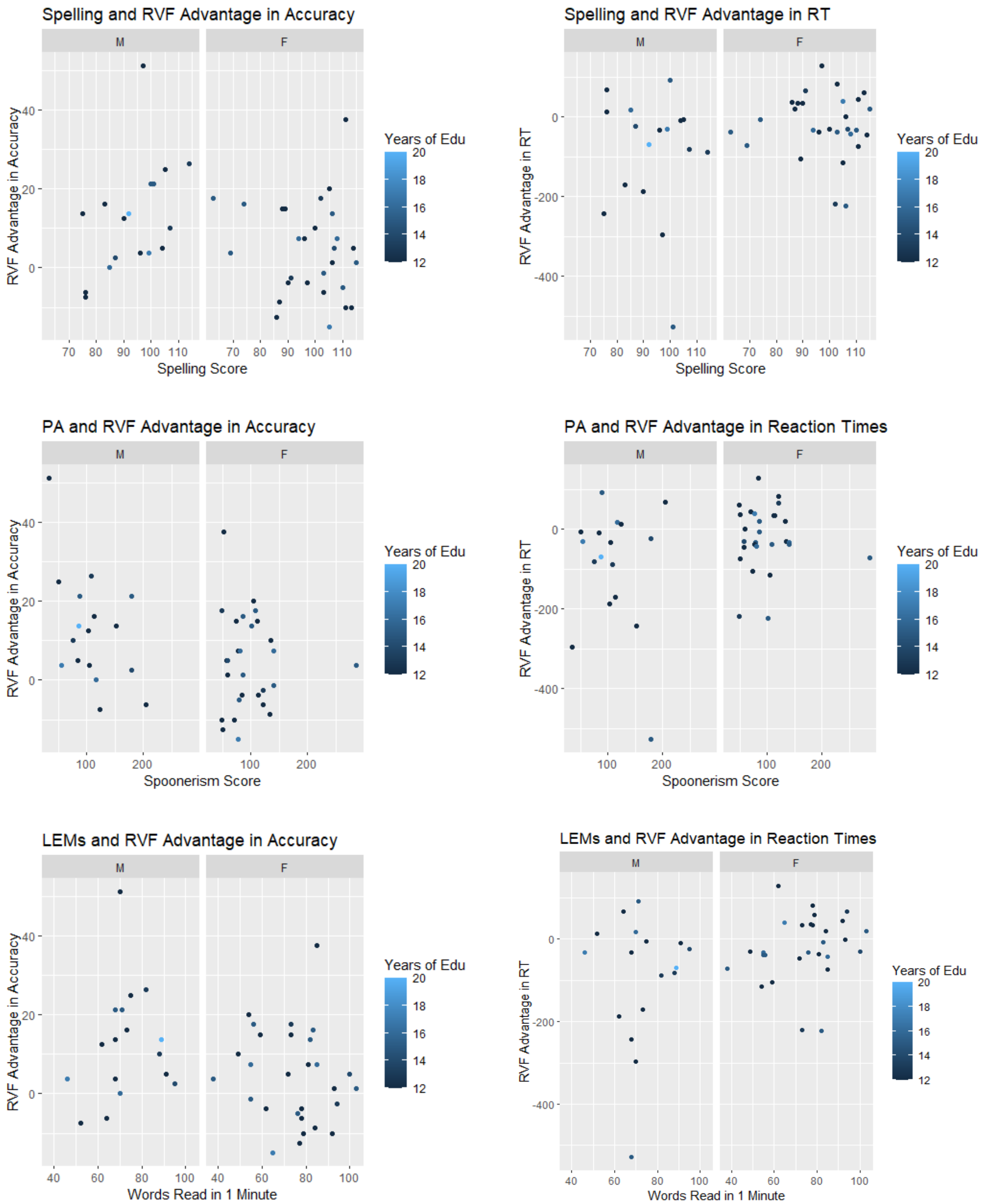
## Appendices

**Figure 1**

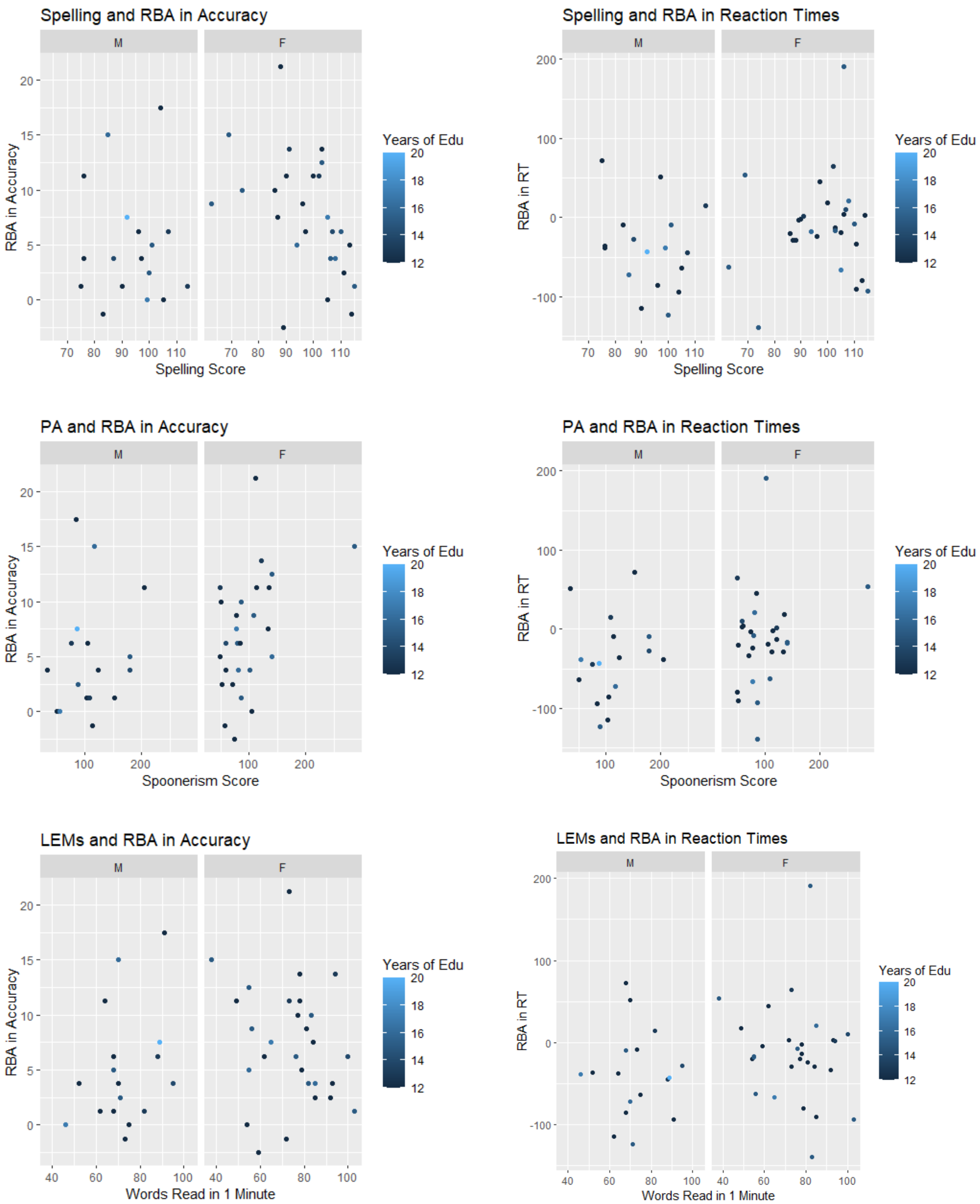
*Correlations Between RVF Advantage and Spelling and Reading Abilities*




*Notes:* Scatterplots of the correlation between the RVF advantage based on accuracy and reaction times, and the independent reading and spelling tests, taking into account gender (M = male, F = female) and the number of years of education. RVF= right visual field, Years of Edu= number of years of formal education, RT= reaction time, PA= phonological awareness, LEMs= Leestest 1-minuut studenten (Word Reading Test for students)

**Figure 2**

*Correlations Between the RBA and Spelling and Reading Scores*




*Notes:* Scatterplots of the correlation between the RBA based on accuracy and reaction times, and the independent reading and spelling tests, taking into account gender (M = male, F = female) and the number of years of education. RBA= redundant bilateral advantage, Years of Edu= number of years of formal education, RT= reaction time, PA= phonological awareness, LEMs= Leestest 1-minuut studenten (Word Reading Test for students)