

Slow perceptual processing at the core of developmental dyslexia: A parameter-based assessment of visual attention

Prisca Stenneken^{a,*}, Johanna Egetemeir^a, Gerd Schulte-Körne^b, Hermann J. Müller^c,
Werner X. Schneider^d, Kathrin Finke^c

^a *Clinical Linguistics & Center of Excellence 'Cognitive Interaction Technology' (CITEC), Bielefeld University, Universitätsstr. 25, D-33615 Bielefeld, Germany*

^b *Department of Child and Adolescent Psychiatry, Psychosomatics and Psychotherapy, University of Munich, Pettenkoferstr. 8a, 80336 Munich, Germany*

^c *Department Psychology, General and Experimental Psychology/Neuro-Cognitive Psychology, Ludwig Maximilians University Munich, Leopoldstr. 13, 80802 Munich, Germany*

^d *Neuro-Cognitive Psychology & Center of Excellence 'Cognitive Interaction Technology' (CITEC), Bielefeld University, Universitätsstr. 25, 33615 Bielefeld, Germany*

ARTICLE INFO

Article history:

Received 14 January 2011

Received in revised form 18 August 2011

Accepted 23 August 2011

Available online 31 August 2011

Keywords:

Developmental dyslexia

Visual attention

Processing speed

Spatial bias

Whole-report

Partial-report

ABSTRACT

The cognitive causes as well as the neurological and genetic basis of developmental dyslexia, a complex disorder of written language acquisition, are intensely discussed with regard to multiple-deficit models. Accumulating evidence has revealed dyslexics' impairments in a variety of tasks requiring visual attention. The heterogeneity of these experimental results, however, points to the need for measures that are sufficiently sensitive to differentiate between impaired and preserved attentional components within a unified framework. This first parameter-based group study of attentional components in developmental dyslexia addresses potentially altered attentional components that have recently been associated with parietal dysfunctions in dyslexia. We aimed to isolate the general attentional resources that might underlie reduced span performance, i.e., either a deficient working memory storage capacity, or a slowing in visual perceptual processing speed, or both. Furthermore, by analysing attentional selectivity in dyslexia, we addressed a potential lateralized abnormality of visual attention, i.e., a previously suggested rightward spatial deviation compared to normal readers. We investigated a group of high-achieving young adults with persisting dyslexia and matched normal readers in an experimental whole report and a partial report of briefly presented letter arrays. Possible deviations in the parametric values of the dyslexic compared to the control group were taken as markers for the underlying deficit.

The dyslexic group showed a striking reduction in perceptual processing speed (by 26% compared to controls) while their working memory storage capacity was in the normal range. In addition, a spatial deviation of attentional weighting compared to the control group was confirmed in dyslexic readers, which was larger in participants with a more severe dyslexic disorder. In general, the present study supports the relevance of perceptual processing speed in disorders of written language acquisition and demonstrates that the parametric assessment provides a suitable tool for specifying the underlying deficit within a unitary framework.

© 2011 Elsevier Ltd. All rights reserved.

1. Introduction

Developmental dyslexia is a complex disorder of reading and spelling acquisition with a rather heterogeneous clinical appearance. The behavioural diagnosis is based on impaired reading and spelling performance in the presence of normal intellectual ability and adequate reading instruction. While there is strong evidence for a genetic basis of developmental dyslexia (for a recent overview see Scerri & Schulte-Körne, 2010), the cognitive causes underlying

the behavioural symptoms, i.e., the latent endophenotypes, have been intensely debated.

Studies aiming to identify cognitive profiles in dyslexia on the one hand confirm the widely accepted notion of a deficit in phonological processing and/or phonological awareness (e.g., Ramus et al., 2003); on the other hand they have accumulated evidence that at least subgroups of dyslexics have profound impairments in non-phonological, attention-based tasks (e.g., Heim et al., 2008; Menghini et al., 2010; Morris et al., 1998; White et al., 2006). Comprehensive reviews of the neural basis of dyslexia (e.g., Habib, 2000; McCandliss & Noble, 2003) indicate that the impairments in representation, storage and retrieval of speech sounds and words are in line with findings of structural brain anomalies and/or altered activation in left perisylvian regions, including Broca's and Wernicke's

* Corresponding author. Tel.: +49 0521 106 6928; fax: +49 0521 106 6447.

E-mail address: prisca.stenneken@uni-bielefeld.de (P. Stenneken).

areas, and in temporoparietal regions, including supramarginal and angular gyri. More specifically, critical characteristics of dyslexia have been suggested to include parietal hypoactivation, morphological changes in asymmetry of the parietal lobes or atypical fibre orientation in circuits including the parietal cortex (e.g., [Habib & Robichon, 1996](#); [Hoefl et al., 2007](#); [Rimrodt, Peterson, Denckla, Kaufmann, & Cutting, 2010](#)). Parietal dysfunction leads to impairments beyond the phonological domain. It is generally assumed to limit the amount of available attentional resources of the brain, thereby reducing perceptual processing speed and working memory storage capacity, and, when asymmetric, to induce a spatial bias of attentional selection towards one hemifield (e.g., [Bublak et al., 2005](#); [Duncan et al., 1999](#); [Finke, Bublak, & Zihl, 2006](#); [Husain & Rorden, 2003](#); [Kerkhoff, 2001](#)). Moreover, electrophysiological and neuroimaging studies have revealed altered brain activation to be related to impaired performance not only in written language tasks but also in more basic auditory or visual processing (e.g., [Peyrin, Démonet, N'Guyen-Morel, Le Bas, & Valdois, 2011](#); [Shaywitz et al., 1998](#)).

However, to date it is not clear whether and to what degree the various potential dysfunctions of the parietal lobe could account for the dyslexic deficits. Systematic investigations are needed that address the different attentional components in an independent manner within the same dyslexic participants and in a unitary framework. Therefore, the present study was designed to systematically assess whether and to what degree adults with dyslexia would show impairments in visual attention, as indicated by different attentional parameters derived from multi-element processing tasks.

Impairments in tasks of multi-element processing, which presents a fundamental requirement in visual word processing, have repeatedly been documented in dyslexia (e.g., [Bosse, Tainturier, & Valdois, 2007](#); [De Luca, Burani, Paizi, Spinelli, & Zoccolotti, 2010](#); [Hawelka & Wimmer, 2005](#); [Jones, Branigan, & Kelly, 2008](#); [Pammer, Lavis, Hansen, & Cornelissen, 2004](#); [Romani, Tsouknida, di Betta, & Olson, 2011](#); [Valdois et al., 2003](#)). Multi-element or string processing deficits are assumed to affect the processing of letter sequences or sublexical units, leading to a marked slowing in written language performance. For example, [Bosse et al. \(2007\)](#) conducted a letter-report task with dyslexic children in order to investigate the visual attentional span performance, estimated as the number of letters accurately reported. This report task, based on [Averbach and Sperling \(1968\)](#), included displays of five letters that were presented for 200 ms and required participants to report all letters (whole report) or one of the letters that was cued after presentation (partial report). The visual attentional span was significantly reduced in the dyslexic children compared to controls and accounted for a substantial amount of variance in reading speed and accuracy. A relation between multi-element processing and reading performance is additionally supported by a study of [Prado, Dubois, and Valdois \(2007\)](#), who showed that a reduced span was associated with an increased number of rightward fixations in text reading, and by a study of [Hawelka and Wimmer \(2005\)](#), who found that a lower performance in multi-element processing was related to an increased number of eye movements in word and pseudoword reading. Recently, the dyslexic visual span disorder has been related to parietal lobe underactivation ([Peyrin et al., 2011](#)). Reviews of neurological/neuroimaging and neurophysiological evidence in dyslexia have pointed to an incapacity of the brain in performing all kinds of tasks requiring processing of brief or sequential stimuli ([Habib, 2000](#); [Schulte-Körne & Bruder, 2010](#)).

Assuming parietal dysfunction as the basis at the neural level, plausible core disorders at the cognitive level would be deficient general attentional resources, involving processing speed and/or working memory storage capacity, as well as anomalies in spa-

tial selection processes. Notably, both of these deficits would be expressed in a variety of perceptual tasks, and especially in multi-element processing tasks, as used in the above studies. The specific goal of the present study therefore was to investigate, whether dyslexic persons would show deficient attentional processing as indicated by slowing of visual perceptual speed and/or reductions in working memory storage capacity, whether they would exhibit a deviation in the spatial distribution of selective attention; or whether they would display a combination of these non-lateralized attentional deficits and of spatially lateralized selection processes.

Theoretical concepts related to speed and/or storage capacity aspects of visual attention are various, including the suggestion of a visual attentional span deficit ([Bosse et al., 2007](#); [Peyrin et al., 2011](#)), a narrowed visual attentional window ([Valdois, Bosse, & Tainturier, 2004](#)), a global change in speed of processing ([Kail & Hall, 1994](#)), a deficit in string-specific or multi-element processing ([Hawelka & Wimmer, 2005](#); [Whitney & Cornelissen, 2005](#); but see [Hawelka & Wimmer, 2008](#) for a discussion of the attentional basis of these deficits) or a general working memory dysfunction ([Ludwig et al., 2009](#)). Importantly, the related experimental paradigms do not permit the impact of a potentially reduced rate of parallel information uptake vs. that of a potentially reduced capacity of a working memory store to be precisely differentiated.

Alternative models, focusing on the selectivity aspects of visual attention, have related the poor multi-element processing performance in dyslexia to an imbalance in the spatial distribution of attention. It has been suggested that developmental dyslexics might show a left mini-neglect, a spatial bias leading to left-sided processing insufficiencies, analogous to the more severe left-sided inattention associated with acquired right-sided parietal brain-injury (e.g., [Kerkhoff, 2001](#)). A crucial observation ([Hari, Renvall, & Tanskanen, 2001](#); [Sireteanu, Goertz, Bachert, & Wandert, 2005](#); [Waldie & Hausmann, 2010](#)) has been that children and adults with developmental dyslexia fail to show the “pseudoneglect” typically observed in unimpaired participants as a slight leftward asymmetry in spatial attention, e.g., in standard line bisection tasks showing a tendency to bisect the line slightly to the left of the centre ([Bowers & Heilman, 1980](#)). Furthermore, difficulties in inhibiting peripheral information in the right visual field have been reported in dyslexics when the task is to focus attention on the centre of gaze ([Geiger, Jerome, & Zegarra-Moran, 1992](#)). Up to now, findings in favour of a left mini-neglect in developmental dyslexia have been provided by a large number of studies using a variety of different tasks (e.g., [Buchholz & Davies, 2005](#); [Facoetti & Molteni, 2001](#); [Facoetti & Turatta, 2000](#); [Facoetti et al., 2003, 2006](#); [Hari et al., 2001](#); [Liddle, Jackson, Rorden, & Jackson, 2009](#); [Ruffino et al., 2010](#); [Sireteanu et al., 2005](#); [Ziegler, Pech-Georgel, Dufau, & Grainger, 2010](#)). The dyslexic deviation in the spatial distribution of attentional resources might account for reading errors, such as omissions of letters or words and letter substitutions or transpositions, and would extend clinical and experimental findings from certain forms of reading disorders associated with parietal lobe lesions ([Di Pellegrino, Ládavas, & Galletti, 2002](#); [Kinsbourne & Warrington, 1962](#); [Stenneken, van Eimeren, Jacobs, Keller, & Kerkhoff, 2008](#)). While the latter study of a form of acquired dyslexia (neglect dyslexia) has pointed to a stronger spatial deviation in more severe dyslexics, a potential relationship between the extent of the spatial deviation and that of the reading disorder has not been addressed quantitatively in developmental dyslexia.

The present investigations consequently required a methodological basis that allows both to identify and to quantify separable attentional components in dyslexia. An ideal approach is provided by the conceptual framework of the Theory of Visual Attention (TVA; [Bundesen, 1990, 1998](#)). Recently, a pioneering dyslexia study ([Dubois et al., 2010](#)) used the TVA-framework in order to disentangle the impact of the potential parietal dysfunctions in a

psychophysical whole-report task of briefly presented letters. In two children with dyslexia, the common impairment revealed was a reduction of the rate of information intake, while only one child additionally suffered from a reduced working memory storage capacity.

The explanatory power of the TVA framework has received further support from studies of other types of impaired letter or word processing. Duncan et al. (2003) identified slowed visual processing as the core deficit in simultanagnosia, a condition characterized as the inability to process multiple elements simultaneously with a large impact on reading performance, which is in some forms related to parietal brain injury. Further extensive TVA-based studies have identified slow visual processing and reduced working memory storage capacity in patients with pure alexia (Starrfelt, Habekost, & Leff, 2009; Starrfelt, Habekost, & Gerlach, 2010), characterized by slow and effortful (letter-by-letter) reading associated with lesions in the area of left mid-fusiform gyrus. Overall, the TVA has a long tradition of development and empirical testing, including a neural interpretation on the basis of the single-cell literature (Bundesen, Habekost, & Kyllingsbæk, 2005). It provides a highly sensitive tool for the assessment of even minor clinical symptoms (Habekost & Bundesen, 2003) and has been well established in the investigation of behavioural correlates of brain dysfunctions (review in Habekost & Starrfelt, 2009).

Within the TVA framework, the visual selection process can be expressed by parameter estimates (for a comprehensive description of the theory's assumptions see Bundesen, 1990; a detailed formal description and the equations of TVA are given by Kyllingsbæk, 2006), each derived from modelling the participants' performance in simple, non-time-critical report tasks with stimuli from multi-element displays (based on Duncan et al., 1999). Participants are briefly (typically not exceeding 200 ms) presented with vertically or horizontally arranged letter arrays and report as many target letters as possible in an un-speeded verbal response. In TVA, selection of an object and its visual features is synonymous with its encoding into a visual working memory store with limited capacity. The probability of selection is determined (i) by an object's attentional weights (w) that each object receives and (ii) by the capacity of the working memory store (if the store is filled, the selection process terminates). Hence, TVA provides parameters for characterizing the general processing efficiency of the information processing system (processing rate and storage capacity), and for characterizing specific aspects of attentional weighting, such as, for example, the spatial distribution of attention.

The whole-report task addresses the general attentional resources: perceptual processing speed (C : number of visual elements processed per second) and capacity of the visual working memory store (K : maximum number of elements maintained in parallel). On the basis of individually adjusted presentation durations, the performance of each participant is described as the number of correctly reported letters as a function of the effective exposure duration. The data are fitted by an exponential growth function, in which the processing speed is reflected in the growth parameter (i.e., the rate at which the stimuli can be processed) and the working memory storage capacity is reflected in the asymptote of the growth function. Thus, estimating these parameters permits attentional models of developmental dyslexia to be tested; specifically, it permits differentiating whether deficient visual span performance (e.g., Bosse et al., 2007) is caused by reductions in perceptual processing speed or in working memory storage capacity or both.

A somewhat different task, partial report, permits the spatial distribution of visual attention across the left and right hemifields to be estimated (parameter w_λ). In this task, participants are required to identify only target letters (e.g., red letters) and ignore distractors (e.g., green letters). The TVA model produces estimates

of attentional weights w_i separately for the left (w_L) and the right hemifield (w_R) and w_λ is then computed as w_L : ($w_L + w_R$). Hence, a value of $w_\lambda = 0.5$ indicates balanced weighting; values of $w_\lambda > 0.5$ indicate a leftward and values of $w_\lambda < 0.5$ a rightward bias. Thus, this paradigm allows for a parameter-based assessment of the contribution of a potential lateralized deficit which has not been provided by studies of developmental dyslexia so far. If adult dyslexics indeed show a spatial "mini-neglect" of the left side of space, this would be indicated by smaller values of w_λ for the experimental compared to the control group, reflecting relatively lower weights for objects to the left of fixation.

Importantly, the estimation of parameters based on the TVA provides quantitative measures of performance, which—in comparison to previous investigations of dyslexia—rely on a set of independent and latent attentional functions or processes. Thus, the TVA framework has the potential for identifying aspects of cognitive functioning that contribute to deficits in (at least subgroups of) developmental dyslexia. Specifying aspects of dysfunction, beyond phonological processing or awareness deficits, would have clinical implications for both assessment of and intervention in developmental dyslexia.

The present group study was designed to systematically assess the specific contribution of different attentional parameters to the multi-system deficit underlying developmental dyslexia. Therefore, parameter estimates in high-achieving young adults with persisting dyslexia were compared to an age- and education-matched control group in order to identify which (combination of) parameters would serve as markers for the underlying deficit. Furthermore, to assess the clinical relevance of the TVA-based parameters, the parameter estimates were correlated with indices of the severity of the dyslexic symptoms.

2. Materials and methods

2.1. Participants

Data from 23 participants (11 females, 12 males) with an average age of 24.87 years (SD 4.41) were entered into analyses. A group of 28 dyslexic adults with persisting dyslexia had been recruited at universities and institutes of higher education, and was screened for the presence of dyslexic symptoms. Throughout their school career, all had experienced reading and spelling difficulties that met ICD-10 diagnostic criteria (World Health Organization, 2007). Four persons did not meet the inclusion criteria (see below) and one person had to be excluded due to response tendencies (increasing proportion of null-responses with advancing duration of the two sub-sessions of testing). All participants had a high educational level (on average 12.61 years of schooling, SD 0.78) and all had passed the German 'Abitur' certificate with good success and most of them (20 dyslexic participants) were enrolled in university programs. Further inclusion criteria in the dyslexic group were persisting developmental dyslexia and normal or above-average intellectual ability (see below). None of the participants met the diagnostic standards of the *Diagnostic and Statistical Manual of Mental Disorders* (DSM-IV; American Psychiatric Association, 2000) for the symptoms of inattention or hyperactivity-impulsivity, and none showed evidence of ADHD according to the Conners' Adult ADHD Rating Scales (CAARS; Conners, Erhardt, & Sparrow, 1999). Average CAARS T -scores were 54.65 (SD 7.54), with T -scores in all participants below 75. Nevertheless, in order to control our results for possible effects of subclinical ADHD symptoms on the TVA parameter estimates, we correlated the CAARS values to the actually affected TVA parameters in the dyslexic group and, furthermore, compared the parameter results in two equal-size subgroups with higher vs. lower CAARS scores.

The control group comprised 23 participants, selected from a larger data pool of unimpaired young adults and matched to the present dyslexic group according to age (25.04, SD 4.71), gender (13 females, and 10 males) and years of schooling (12.83, SD 0.65; all had passed the German 'Abitur' certificate with good success and were enrolled in university programs). Participants were screened to exclude neurological, cognitive and developmental disorders, all had normal or above-average intellectual ability (see below), normal reading and spelling abilities and no signs of attention-deficit hyperactivity disorder (ADHD). None of the participants met the diagnostic criteria of the *Diagnostic and Statistical Manual of Mental Disorders* (DSM-IV; American Psychiatric Association, 2000) or of the ICD-10 (World Health Organization, 2007) for the symptoms of inattention or hyperactivity-impulsivity deficits or for the symptoms of reading and spelling disorders, which were therefore not psychometrically assessed.

Both, the dyslexic and the control group underwent an assessment of general intellectual ability (MWT-B; Lehl, 1999). This vocabulary test, which presents a standard procedure in German norm-referenced assessment, resulted (as expected due to the verbal nature of the test) in a lower performance in dyslexics (M 102.04, SD 9.80) than controls (M 120.14, SD 11.32). Due to fairness of testing, additional non-verbal assessment of general intellectual ability (CFT 20; Weiß, 1998) was administered in the dyslexic group, which revealed average or above-average non-verbal intelligence in each participant (M 122.00; SD 7.99). Further inclusion criteria in all participants were normal or corrected to normal vision and intact colour perception, no impairments of productive language (according to ICD-10) and no history of neurological or psychiatric deficits. All participants were monolingual native-German speakers, had attended regular schools and received conventional reading instruction. All participants gave informed consent to participate in the study, which conformed to the ethical standards of the Declaration of Helsinki.

2.2. Written language assessment

In addition to the screening procedure, a psychometric written language assessment was administered in the dyslexic group with a standardized instrument which provides normative data for German-speaking adults in the age-range of the present study (*Rechtschreibungstest, R-T.*; Kersting & Althoff, 2004). In German, which has a rather regular orthography and a high consistency in grapheme–phoneme relations, tests of spelling performance are considered to have high sensitivity compared to reading tests. Moreover, spelling impairments often persist into adult life even after reading performance has improved (World Health Organization, 2007). Results show a marked impairment in dyslexics (average T -score 35.70, SD 6.87), with written language performance lower than would be expected from the general intellectual ability scores.

Reading performance was assessed in the screening procedure and in additional testing with reading lists, as no normative data are available for the present age group. The screening revealed that the majority of dyslexic participants experienced consistent problems with reading aloud of longer text passages, whereas silent text reading abilities improved with practice or compensating strategies. Results from two clinically well-established reading lists (Word and Pseudoword Reading List, Schulte-Körne, 2001; 1-Minute Reading Fluency Test, Willburger & Landerl, 2009), requiring the participants to read words and pseudowords as fast and correctly as possible, revealed a profound deficit in pseudoword reading in the present dyslexic sample. The dyslexics' performance on the list of 48 words and 48 pseudowords (Schulte-Körne, 2001) was compared to available results (from Schulte-Körne, Bartling, Deimel, & Remschmidt, 2004) for normal readers ($n = 28$), matched to the present dyslexics for age (M 27.54 years, SD 6.17) and intellectual ability (M 117.39, SD 13.66). Performance was considerably reduced in dyslexic participants, with a more pronounced impairment for pseudowords (correctly read items per second in dyslexics: M 0.42, SD 0.12, normal readers: M 0.55, SD 0.13; $t(49) = 3.52$, $p = 0.001$) than for words (dyslexics: M 1.11, SD 0.25; normal readers: M 1.26, SD 0.30; $t(49) = 2.00$, $p < 0.051$). For the 1-Minute Reading Fluency Test, norm population samples were available only up to the 4th grade (Willburger & Landerl, 2009) and were used here for illustrative purposes: Only with word stimuli did the dyslexics' performance (correctly read items per minute: M 103.39, SD 18.61) exceed that of 4th-grade normal readers (M 79.64, SD 18.19), whereas with pseudoword stimuli (M 53.43, SD 14.91) the dyslexics' performance resembled only the level of 4th-grade normal readers (M 46.75, SD 12.27), corresponding to a performance disadvantage of at least 8 years of school education. Additional details of the dyslexic participants' reading and spelling performance are given in Appendix A.

Letter identification and naming performance was assessed in the dyslexic sample, although the experimental tasks did not require speeded responses and all dyslexics had an above-average educational background. Presented with a sheet of paper containing the 27 letters that were used in the report tasks (randomly arranged in three rows), all participants were able to name the letters fluently and correctly.

2.3. Experimental design

All participants performed computer-based whole- and partial-report tasks in a fixed order within a single testing session. The two report tasks had a duration of 30 min each and were separated by a small break. The general method and stimuli were similar to those used in previous studies (Duncan et al., 1999; Finke, Bublak, Dose, Müller, & Schneider, 2006). Stimuli were presented on a 17" computer monitor (1024 × 768-pixel screen resolution, 70-Hz refresh rate). Viewing distance was kept constant at about 50 cm by using a chin rest. Participants were tested individually in a dimly lit room with constant lighting conditions checked via luminance meter measurements. At the start of each trial, participants fixated a central white fixation cross presented for 300 ms on a black background, followed, after a blank screen of 100 ms, by displays with red and/or green letters (0.5° high × 0.4° wide). On a given trial, each letter appeared only once and was randomly chosen from the following set {ABEFHJKLMNPRSTWXYZ}. Each participant received the same letter displays in the same order. Stimuli were either unmasked or followed by masks, i.e., squares of 0.5° filled with '+' and 'x' presented for 500 ms at each stimulus location. In unmasked conditions, the effective exposure durations are prolonged by several hundred milliseconds due to 'iconic' memory buffering (Sperling, 1960). The post-array masks

were shown to terminate the iconic letter representation. The individual duration of iconic memory buffering in ms is a further free variable, μ , which is estimated for each participant and which is assumed to be constant across various experimental conditions. Although the latter assumption might be only an approximation (see Di Lollo, 1980 for evidence that visual persistence varies with exposure duration) close fits between modelling and empirical data in various studies (for an overview see Habekost & Starrfelt, 2009) suggest that this assumption is appropriate at least for the whole report paradigm used in this study.

In order to avoid potentially confounding influences of saccadic eye movements, relatively short exposure durations (i.e., below or around 200 ms) were used. Only the longest exposure duration in the whole report exceeded 200 ms in some of the participants. This was necessary in order to ensure that all participants were actually able to fill their working memory stores up to their individual limits. Note, however, that estimations of speed and laterality relied critically on performance in trials with shorter exposure durations. Participants were instructed to verbally report, with no time limits, only those letters they were sure to have recognized.

2.3.1. Whole report

Stimuli were arranged in a column of five equidistant letters, either all red or all green, presented 2.5° of visual angle to either the left or to the right of fixation (Fig. 1A). An initial test phase of 24 trials with masked stimuli was used to determine the individual exposure duration at which the participant could report, on average, one letter correctly. This value was then introduced as intermediate experimental exposure duration, together with a shorter (half as long) and a longer (twice as long) exposure duration, in either masked or unmasked conditions. The resulting six 'effective' exposure durations were introduced to sample response accuracy across a broad performance spectrum. The adjusted average exposure durations obtained in this way for the dyslexic group were 53, 104 and, respectively, 210 ms. Letter displays in the experiment proper were presented either masked or unmasked, resulting in twelve different trial conditions (2 hemifields × 3 exposure durations × 2 masking conditions), each with 16 trials (overall 192 trials).

2.3.2. Partial report

Stimuli were presented at the corners of an imaginary square with an edge length of 5° and comprised either a single target, or two stimuli arranged either horizontally or vertically. Displays of two stimuli contained either a target plus a distractor, or two targets. Letter stimuli were always masked (Fig. 1B). Participants were instructed to report only the targets (red letters) and ignore the distractors (green letters). The initial test phase comprising 32 trials was used to determine the individual exposure duration, aiming for about 80% accuracy on single-letter trials. This yielded an average exposure duration of 107 ms for the dyslexic group, and of 77 ms for the control group. In the experiment proper, this exposure duration was used for all trials. The experiment comprised 16 different conditions (4 single-target, 8 target plus distractor, and 4 dual-target conditions) with 18 trials each (overall 288 trials).

3. Experimental results

The results of the parameter estimates are presented below for the whole-report (perceptual processing speed, working memory storage capacity) and the partial-report task (spatial laterality of attentional weighting). First, we describe the qualitative pattern of performance as well as the degree of correspondence between the observed data and the TVA parameter estimates (the model fitting procedure was largely identical with Duncan et al., 1999). Then, we present and compare the parameter estimates obtained for each group. In order to assess the clinical relevance of the TVA markers, we correlate the actually affected TVA parameters (i.e., parameters showing a deviation of the dyslexic group from the control group) to the severity of dyslexic impairment. To control for an influence of subclinical ADHD symptoms, further analyses focus on the dyslexic participants' TVA estimates in relation to the CAARS values.

Additional analyses were conducted addressing the possibility that different response criteria might have been adopted by the participants. For example, a less conservative response criterion could have affected the probability that participants' responses included distractors in the partial report task and result in the general tendency to make guesses. Therefore, the error proneness of participants was analysed, estimated as the probability of reporting an incorrect letter, i.e., distractors or letters not included in the display (cf. Vangkilde, Bundesen, & Coull, *in press*). Results revealed highly comparable values in the two groups, both in the whole report (on average in dyslexics: 19%, controls: 20%, $p > 6$) and in the partial report (dyslexics: 19%, controls: 17%, $p > 2$), confirming

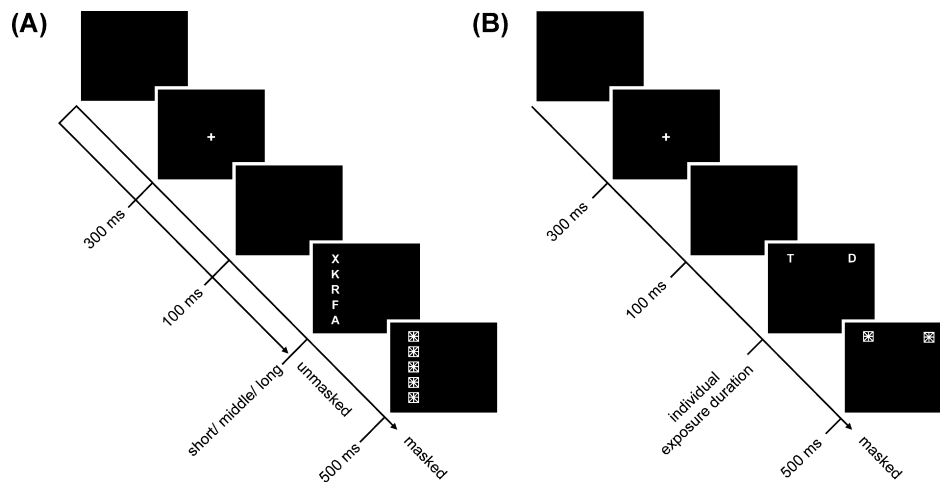


Fig. 1. Example of a trial in the whole-report (A) and the partial-report (B) paradigm (based on Bublak, Redel, & Finke, 2006). In the whole report, five equidistant letters were presented in columns either on the left or the right of a preceding central fixation point, with or without additional masking stimuli. In the partial report, 16 trial types were used: 4 single target ('T', always in red colour) and 4 dual target conditions and 8 conditions of a target with a distractor ('D', always in green).

that participants of both groups performed in the pre-determined accuracy range and, more importantly, adopted similar response criteria.

3.1. Whole-report results

3.1.1. Response accuracy

To illustrate the whole-report results, the performance of two representative participants is shown in Fig. 2. In each graph, the observed number of correctly reported letters [$Mean(obs)$] as a function of the effective exposure duration t is presented separately for the left and the right hemifield. Along with the observed data points, the maximum likelihood fits (e.g., Ross, 2000), on which the TVA parameter estimates are based, are presented as solid lines [$Mean(theo)$], indicating a close correspondence between the theoretically predicted and the observed mean scores. In the exponential growth functions the slope at the point ($t_0, 0$) reflects the rate at which the presented stimuli are processed (perceptual processing speed C in elements per second), and the asymptote indicates the maximum number of objects that can be represented in parallel (working memory storage capacity K as the maximum number of letters reported on any single trial).

In the graphs of both participants, the functions initially exhibit the steepest rise. However, the increases in the dyslexic participant's curves are shallower than those in the control participant in both hemifields, indicative of a bilateral speed impairment. As exposure duration increases further, both functions approach a comparable asymptotic level of around 3.5–4 letters, indicative of a similar level of working memory storage capacity.

3.1.2. Parameter estimates

For the whole-report task, for each participant, quantitative estimates were obtained from the TVA model fitting procedure for the parameters processing speed and visual working memory capacity. Processing speed estimates were computed separately for the left and the right visual field (C_L and C_R) from the summed v -values of all letters presented in respective hemifield. Likewise, working memory storage capacity K was estimated separately for the left (K_L) and the right (K_R) visual field. The average Pearson correlation coefficients r for the TVA's best fit to the data and the observed mean values in the different experimental conditions were 0.87

(SD 0.12) for the dyslexic group and 0.90 (SD 0.05) for the control group.

3.1.2.1. Perceptual processing speed. Parameter estimates for processing speed (C) over both visual fields were 19.16 (SD 7.05) in the dyslexic group and 25.92 (SD 7.87) in the control group. An ANOVA with the between-subject factor *group* (dyslexics, controls) and the within-subject factor *side of visual field* (left, right) revealed a significant group effect ($F(1, 44) = 9.43, p = 0.004$), indicating processing speed to be severely reduced in dyslexic participants (by around 26% compared to controls). The within-subject factor *side of visual field* was significant ($F(1, 44) = 18.77, p < 0.001$), reflecting a small advantage for the right over the left visual field in both groups. No significant interaction between the two factors was observed ($p = 0.271$), confirming that the perceptual slowing in the dyslexic group is a bilateral deficit (Fig. 3A).

3.1.2.2. Visual working memory storage capacity. Parameter estimates for *visual working memory storage capacity* K over both visual fields were 3.43 (SD 0.54) in the dyslexic group and 3.28 (SD 0.59) in the control group. An ANOVA revealed non-significant results for the between-subject factor *group* ($p = 0.357$) and the within-subject factor *side of visual field* ($p = 0.290$). Also the interaction of the two factors failed to reach significance ($p = 0.090$). Thus, the storage capacity did not show any lateralization and, more importantly, was comparable between the dyslexic and the control participants (Fig. 3B).

Additional meta-analyses were performed, taking the individual distribution of parameter values of C and K in dyslexic and control participants into account. Each participant's data set was re-sampled 200 times by a bootstrapping algorithm. By application of the TVA-based maximum-likelihood procedure, this resulted in 200 'new' estimations of the parameters (for methodological details, cf., Habekost & Bundesen, 2003). Fig. 4, as a bivariate scatter plot of processing speed C vs. working memory storage capacity K , shows the individual parameter estimates. Each data point represents a single participant, and horizontal and vertical standard error bars represent the associated individual standard errors (as estimated by the standard deviation of each parameter across the bootstrapping sample). It can be seen that the dyslexic and the control group are separated with respect to processing speed, while working mem-

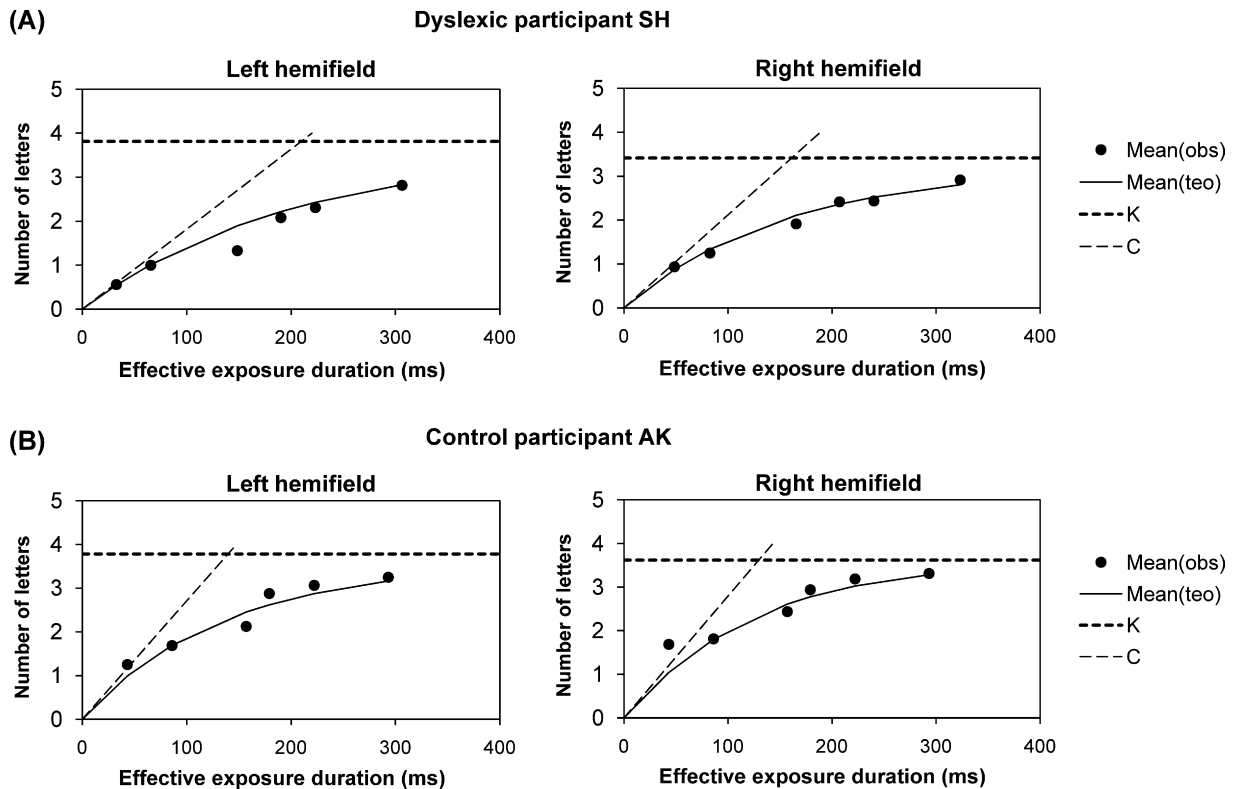


Fig. 2. Whole-report performance in the left and the right hemifield: (A) for a representative dyslexic participant, SH, and (B) for a representative control participant, AK. The mean number of letters reported is shown as a function of effective exposure duration. *Mean(obs)* = observed number of letters reported correctly; *Mean(theo)* = predicted number of letters reported correctly; *K* = visual short term memory storage capacity.

ory storage capacity values are largely overlapping. Furthermore, the standard errors indicate a high robustness of the individual parameter estimates.

3.2. Partial-report results

3.2.1. Response accuracy

The partial-report performance provides the basis for estimating the laterality of attentional weighting across the left vs. the right visual hemifield. This measure of a spatial distribution of attentional weights is illustrated in Fig. 5 for two individual representative participants from the dyslexic and control groups (cf. also Fig. 2) in terms of the mean proportions of target letters correctly identified. The control participant's performance for the left and right side reveals slight visual field differences between unilateral and bilateral stimulus presentations; by contrast the dyslexic participant shows highly similar results across both hemifields in all conditions. In bilateral stimulus conditions, critical for the

estimation of the laterality of attentional weighting, the control participant is slightly more accurate for the left-sided compared to the accompanying right-sided target. Thus, when objects in the left and the right hemifields compete for selection (Desimone & Duncan, 1995), an attentional bias or preference for the left visual hemifield indicates a normal, slight pseudoneglect (for review of the phenomenon see Jewell & McCourt, 2000; for evidence from TVA-based studies see Finke et al., 2005; Finke, Bublak, Dose, et al., 2006; Matthias et al., 2010). The dyslexic person seems to deviate from this pseudoneglect pattern in allocating attentional resources in a highly balanced manner to both visual hemifields.

Results across the different experimental conditions in both groups were in accordance with the predictions of the TVA (e.g., Bundesen, 1990): Accuracy was highest in single target conditions and, due to biased competition of stimuli (Desimone & Duncan, 1995), suffered by the addition of a second stimulus. Due to the individual adjustment of presentation durations, performance for single targets was comparable between groups ($t(44)=0.33$,

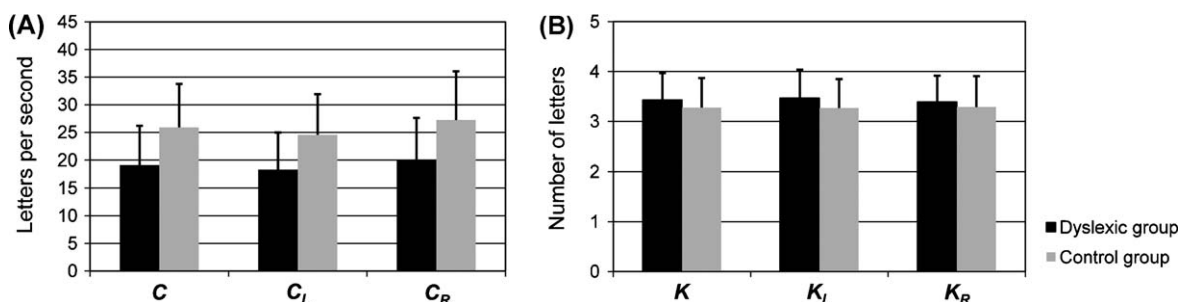


Fig. 3. Average estimates (and standard deviations of the parameter estimates between participants per group) for parameter *C* processing speed (A), and parameter *K* visual working memory storage capacity (B) in the dyslexic group and the control group, for both visual fields, and separately for the left (*C_L*, *K_L*) and the right (*C_R*, *K_R*) side of the visual field.

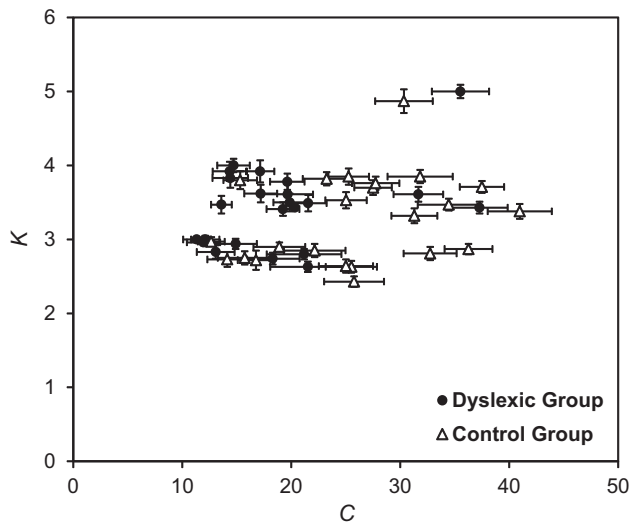


Fig. 4. Bivariate scatter plot of estimates for the parameters processing speed C vs. working memory storage capacity K (as obtained by 200 bootstrap repetitions). Each data point represents a single participant of the dyslexic group (filled dots) or the control group (open triangles), and error bars represent the associated individual standard errors (as estimated by the standard deviation of each parameter across the bootstrapping sample) for C (horizontal bars) and K (vertical bars).

$p = 0.742$). The performance of both the dyslexic group (M 80.22, SD 5.19) and the control group (M 80.83, SD 7.13) reached the pre-defined criterion: accuracy did not differ from 80% level (dyslexic: $t(22) = 0.201$, $p = 0.843$, control: $t(22) = 0.556$, $p = 0.584$).

3.2.2. Parameter estimates

The qualitative pattern of performance in each group was described by TVA estimates, for each participant, of the attentional weights w_i separately for each of the four display locations. The observed mean values in the different conditions and the theoretical predictions of the TVA model showed a good correspondence, with an average Pearson correlation coefficient r between observed and predicted values of 0.74 (SD 0.13) in the dyslexic group and 0.71 (SD 0.18) in the control group.

3.2.2.1. Laterality of sensory effectiveness. To differentiate between true attentional and pure sensory effects of stimulus processing, the TVA model additionally provides parameter estimates for basic sensory effectiveness A which was also estimated for each of the four possible stimulus locations (A_i). The A_i parameters, which are independent of attentional weighting, were derived from the accuracy for each (target) location in the single-target condition (for details see Duncan et al., 1999). Analogous to the computation of the w_λ value for spatial attentional weighting, equal sensory effectiveness of stimuli in both visual hemifields is indicated by an A_λ value of 0.5. A_λ values above and below 0.5 indicate better sensory processing on the left and, respectively, the right side. Mean group parameters (relative sensory effectiveness for both hemifields A_L and A_R , spatial distribution of sensory effectiveness A_λ and spatial distribution of attentional weighting w_λ) from TVA's best fit to each participant's data are shown in Table 1. Parameter estimates for the sensory effectiveness, A_λ , did not differ significantly between the dyslexic and the control group ($t(44) = 1.825$, $p = 0.075$). Moreover, in both groups the average A_λ did not differ significantly from 0.5, i.e., indicative of balanced sensory effectiveness in both hemifields (dyslexic group: $t(22) = 1.04$, $p = 0.310$; control group: $t(22) = 1.50$, $p = 0.147$). Thus, attentional laterality differences in partial-report

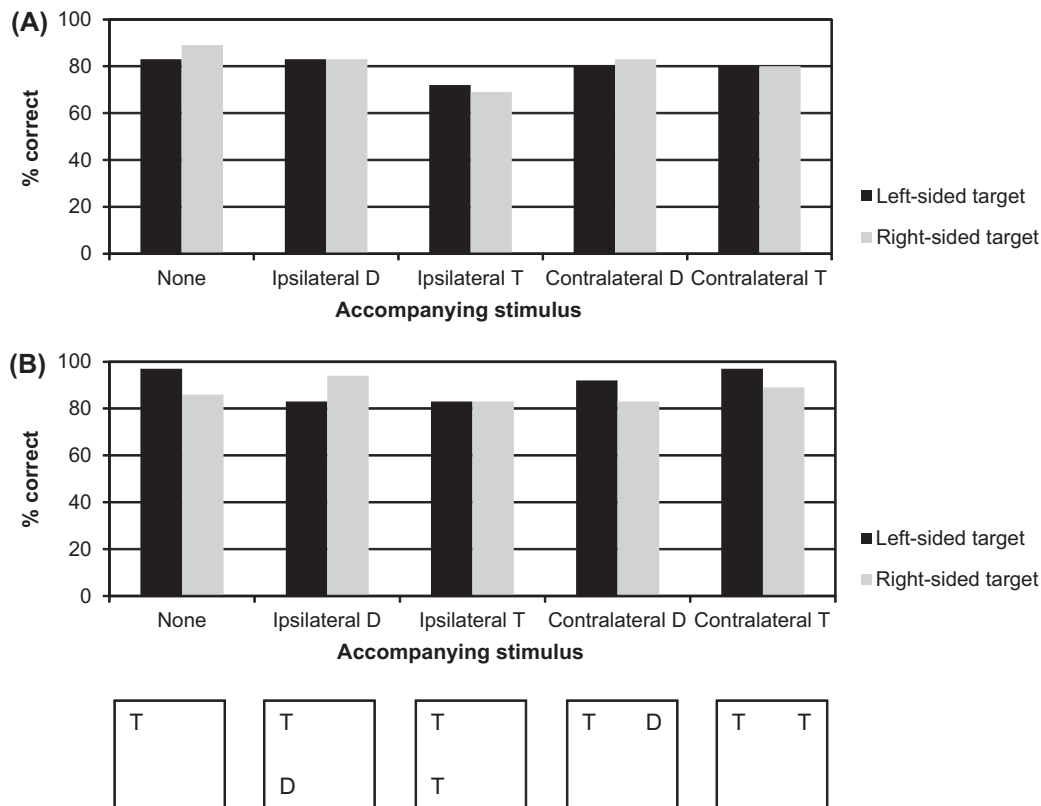


Fig. 5. Percentage of correctly reported targets (with standard deviations): (A) for a representative dyslexic participant, SH ($w_\lambda = 0.50$) and (B) for a representative control participant, AK ($w_\lambda = 0.59$). Single targets (T), targets accompanied by an ipsilateral target or distractor (D), and by a contralateral target or distractor. Example displays for left upper targets are presented below.

Table 1

Mean group parameters for relative sensory effectiveness A_L and A_R , spatial distribution of sensory effectiveness A_λ , and spatial distribution of attentional weighting w_λ . A_L and A_R were calculated as the mean value of sensory effectiveness for upper and lower positions on the left and on the right [$A_\lambda = A_L / (A_L + A_R)$]. w_L and w_R were similarly calculated as the mean of attentional weights for the upper and lower positions on the left and on the right [$w_\lambda = w_L / (w_L + w_R)$].

	A_L	A_R	A_λ	w_L	w_R	w_λ
Dyslexic group	2.32 (0.43)	2.24 (0.45)	0.51 (0.04)	0.58 (0.09)	0.59 (0.12)	0.50 (0.04)
Control group	2.46 (0.72)	2.64 (0.76)	0.48 (0.05)	0.58 (0.10)	0.48 (0.16)	0.55 (0.07)

performance would not be confounded by laterality differences in sensory effectiveness.

3.2.2.2. Laterality of attentional weighting. The control group's laterality of attentional weighting, characterized by an average w_λ value of 0.55 showed a slight but reliable leftward bias (pseudoneglect, Fig. 6), with the observed value differing significantly from the unbiased value of 0.5 ($t(22) = 3.72$; $p = 0.001$). In contrast, w_λ estimates in the dyslexic group (average 0.5) were not significantly different from 0.5 ($p = 0.845$) and deviated significantly from those of controls ($t(44) = 3.28$; $p = 0.002$), thus confirming the absence of the normal leftward spatial bias.

3.3. Analyses of clinical relevance and specificity of the results

3.3.1. Clinical indices of dyslexia

Correlations between the severity of the dyslexic reading and spelling impairment and the TVA parameter estimates were computed for the dyslexic group. Significant results were obtained only for the standardized and norm-referenced dyslexia assessment used in the present age-group, i.e., the T -scores of spelling assessment, which correlated significantly with the TVA parameter estimates of the laterality of attentional weighting w_λ ($r = 0.572$; $p = 0.004$; corrections due to multiple testing: $\alpha = 5\%/8 = 0.0065$). This correlation indicates that the lower the written language performance in dyslexics the more their attentional weighting deviates from that of controls to a rightward direction, i.e., a more severe dyslexic deficit is associated with a larger rightward bias (Fig. 7). More specifically, in all dyslexic participants, whose laterality of attentional weighting index differed by 1 SD or more from the mean of the control group ($1 - w_\lambda > 0.52$) also displayed a score in the dyslexia assessment that fell 1 SD or more below the normative mean (T -score < 40). In additional analyses, we controlled for possible effects of the dyslexics' phonological skills on the above correlation. Results confirmed the significant correlation also when taking individual performance as expressed by the composite pseudoword-reading score into account as an additional control variable ($p = 0.004$).

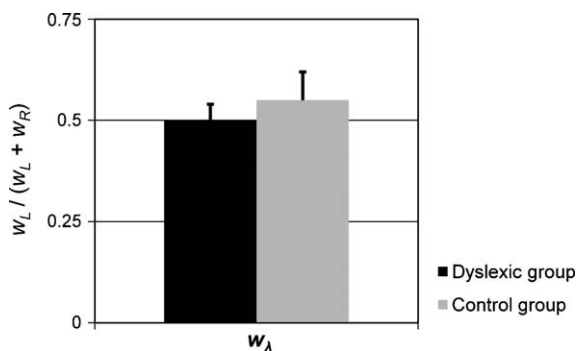


Fig. 6. Average parameter estimates (and standard deviations of the parameter estimates between participants per group) for the laterality of attentional weighting (w_λ) in the dyslexic and control group. A value >0.50 is associated with a leftward bias, a value <0.50 with a rightward bias.

3.3.2. Inter-parameter correlation

The inter-parameter correlations between the affected TVA estimates that could serve as markers for dyslexia (C , w_λ) were non-significant ($r = -0.108$, $p = 0.62$).

3.3.3. Relationship to ADHD symptoms

Scores of the ADHD Rating Scale CAARS were not significantly correlated with the TVA parameter estimates of either perceptual processing speed C or laterality of attentional weighting w_λ (both $p > 0.066$). When additionally comparing the two groups of participants with relatively high and relatively low CAARS T -values (based on median split), no significant group differences were evident in the affected TVA parameters (both $p > 158$).

4. Discussion

Conceptually, the present study has drawn, on the one hand, on the assumptions about behavioural correlates of parietal dysfunction and, on the other hand, on a recent parametric assessment of two single cases suggesting attentional deficiencies in developmental dyslexia (Dubois et al., 2010). The aim was to systematically investigate cognitive components associated with general attentional resources and selectivity aspects in dyslexia and to explore their relation to the severity of the disorder.

4.1. General attentional resources: processing speed and working memory storage capacity

Results concerning the general attentional resources, as assessed by the letter report task, revealed that the visual perceptual processing speed (parameter C) is profoundly impaired in the dyslexic group compared to the group of normal readers. By contrast, the visual working memory storage capacity (parameter K) of the dyslexic group is within the normal range. These results have been established in adults with persisting dyslexia when compared to a control group that was matched according to both, chronological and educational age. Moreover, possible effects of ADHD have been controlled for in the present dyslexic sample. A recent

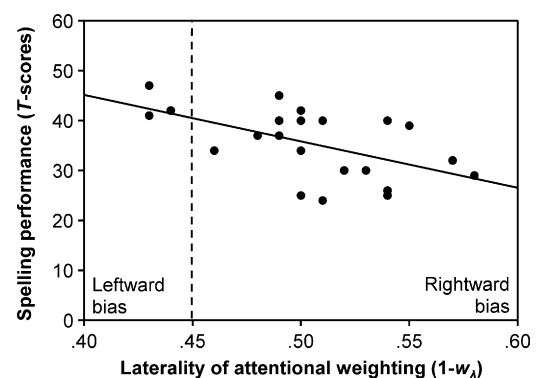


Fig. 7. Correlation of the laterality of attentional weighting (we are using $1 - w_\lambda$ in this figure in order to display a rightward bias on the right side of the figure) with spelling performance (T -scores) in the dyslexic group. Values of $1 - w_\lambda < 0.05$ indicate a leftward bias, values >0.05 indicate a rightward bias. The average value of the control group of 0.45 is displayed as a vertical line.

TVA-based study (Finke et al., *in press*) furthermore suggests that dyslexic and ADHD groups might be separated by TVA parameter estimates, as the group of adults with ADHD in Finke and colleagues demonstrated normal processing speed while working memory storage capacity was markedly impaired.

Most importantly, the present findings from developmental dyslexia permit to disentangle the two parameters of perceptual processing speed and working memory storage capacity, both of which could potentially induce impaired visual span performance and deficiencies in multi-element processing. Based on our results, the deficit in the processing of letter arrays is attributable to impaired visual perceptual processing speed, rather than visual working memory storage capacity. That is, our sample of adult dyslexics displayed a normal span of apprehension (they did not differ from normal readers in the maximum number of letters that they could encode into visual working memory), while being substantially slower in the processing of the letter displays (by around 26% compared to controls).

The finding of a reduction in the total rate of visual information uptake is in line with previous evidence of impaired performance in visual span and multi-element processing tasks (e.g., Bosse et al., 2007; Hawelka & Wimmer, 2005; Jones et al., 2008; Pammer et al., 2004; Romani et al., 2011; Valdois et al., 2003). Note that the apparently unimpaired processing speed as suggested in some studies relates to motor speed or direct task performance measures (e.g., reaction times) and is not to be confounded with the parametric estimates of the rate of visual information uptake, as pointing to underlying potential processing speed deficits. Since in the results of the present dyslexic group the processing speed estimates were reduced equally for letters presented in the left and the right visual field, this finding can be taken to reflect a bilateral and basal slowing in information uptake. A consequence for reading performance would be a slower and less efficient word processing, increasing the time needed for processing each written unit in order to derive the same amount of information as normal readers.

Note that anomalies in saccadic performance, which have been documented in dyslexia (overview in Rayner, 1998), cannot causally account for our results. Since the TVA estimates of perceptual speed relied on the increase in accuracy from visual threshold to very short exposure durations (far below 200 ms), the slow letter processing speed cannot be attributed to the abnormal saccadic performance. The reduction in the perceptual processing speed (by around 26% compared to the control group) represents a profound deficit, which can substantially contribute to the deficient multi-element processing in dyslexics. Furthermore, slow perceptual speed in the dyslexics is rather unlikely to be a secondary consequence of a possibly lower reading practice compared to normal participants, given the high level of academic education achieved in the present dyslexic group.

It could be argued that dyslexics were simply more prone to masking and, therefore, showed reduced letter report in (masked) trials with short effective exposure durations but not in those (unmasked) trials with long exposure durations. However, the TVA framework provides an explicit explanation for possibly increased masking effects in participants with low processing speed: At short exposure durations, masking terminates perception at an earlier state of processing, when the working memory store is far from being filled. In unmasked conditions, with typically several hundred ms added to the effective exposure duration due to iconic memory, a decisive benefit results. Such an effect is less pronounced in participants with a high rate of information uptake, who already perceive more information in short, masked conditions.

With regard to psycholinguistic models of written word processing, the slowing and inefficiency in the simultaneous processing of multi-letter arrays is consistent with an inefficiency in the fast and automatic access to whole words and a reliance,

instead, on a serial, sublexical strategy, as typically adopted by dyslexic readers of regular orthographies (Landerl, Wimmer, & Frith, 1997; Wimmer, 1993). Likewise, reduced visual processing speed (parameter C) has previously been associated with acquired, neurogenic deficits that are characterized by effortful, serial reading (e.g., simultanagnosia, Duncan et al., 2003; pure alexia, Starrfelt et al., 2009, 2010). A serial reading strategy is expected to affect time-critical reading measures and especially measures of pseudoword processing, which in contrast to familiar words, more strongly depends on serial scanning of the letter string. Both slowing and a marked disadvantage for pseudowords are reflected in the results of the reading assessment in the present dyslexic group. Moreover, even with unlimited exposure durations, a reduction in processing rate will decrease the number of elements that can be processed so that this perceptual failure results in an increase in errors, when multiple elements simultaneously compete to be processed (cf., Duncan et al., 2003).

4.2. Attentional selectivity: spatial distribution of attentional weights across hemifields

In the present, systematic assessment of attentional selectivity components in dyslexia based on the partial letter report, we found changes in the spatial distribution of attentional weights (parameter w_λ). While the normal readers showed a typical pseudoneglect, indicated by a slight leftward bias in spatial attentional weighting (Jewell & McCourt, 2000), which has also been documented in several TVA-based studies in unimpaired adults (Bublak et al., 2005; Finke et al., 2005; Habekost & Rostrup, 2006; Matthias et al., 2009, 2010), this effect was absent in the present group of dyslexics. The present finding is consistent with a mild left mini-neglect in developmental dyslexia, i.e., comparatively reduced sensitivity to left-sided information, which has been related to a right parietal lobe dysfunction (Hari et al., 2001; Sireteanu et al., 2005) or to a disturbed communication between parietal structures of the left and right hemispheres (Waldie & Hausmann, 2010). Note that, according to a biased competition assumption (e.g., Desimone & Duncan, 1995) a bias in attentional laterality induces hemifield differences only in bilateral displays, i.e., when stimuli in both visual hemifields compete for access to working memory and those in the preferred hemifield are the stronger competitors. The finding that, in both groups, processing speed and working memory storage capacity is similar across hemifields (as estimated on the basis of unilaterally presented letter columns) is well in line with the finding that the relative sensory effectiveness for both hemifields A_L and A_R , is balanced. To summarise, these findings indicate that attentional laterality differences in partial-report performance are purely attributable to lateralized attentional selection processes and are not confounded by more basic laterality differences in sensory effectiveness.

It is generally assumed that normal reading requires systematic left-to-right (in dextrograde writing systems) allocation of attentional weights (Cestnick & Coltheart, 1999), thus abnormal visuo-spatial processing presents a critical impairment for written language processing. Similarly, disturbances in visuo-spatial word processing are typically observed in acquired deficits that involve parietal damage (e.g., Braet & Humphreys, 2007; Duncan et al., 2003; Shalev, Mevorach, & Humphreys, 2008; Stenneken et al., 2008), suggesting that parietal functioning is critically involved in the visuo-spatial processes during reading.

Again, the deviating spatial distribution of attentional weights in the present dyslexic group cannot be attributed to abnormal visual saccadic behaviour. First, the exposure durations used in our parietal report procedure were very short (i.e., below 200 ms), effectively excluding saccadic eye movements towards one or the hemifield. Second, systematic saccadic deviations towards one side

of the display would have had a major, differential influence on pure sensory processing (i.e., the basic perceptual effectiveness) for stimuli presented in the two hemifields. However, as documented by the parameter estimate indicative of the distribution of sensory effectiveness (A_L, A_R), no such laterality differences were found between groups; instead, in both groups, sensory effectiveness was found to be balanced across the two hemifields.

In the present group of developmental dyslexics, which included participants with mild to moderate degrees of reading disorder, the variance in the disorder's severity allowed us to relate the severity to the degree of change in the TVA parameters. This analysis revealed that the more the spatial distribution in dyslexics deviated from that of controls the more severe their dyslexic disorder, even when controlling for their phonological skills. The findings are in line with those of previous TVA-studies of neurogenic disorders that have related abnormal visuo-spatial processing to severity measures. Peers et al. (2005), in their study of patients with frontal and, respectively, parietal brain lesions showed that the strength of the spatial processing bias was predicted by simple lesion volume: More extensive damage was associated with a stronger attentional imbalance. Similarly, spatial deviations have been found to be correlated with the severity of the underlying genetic pathology in subcortical and cortical neurodegenerative disorders (Finke, Bublak, Dose, et al., 2006; Redel et al., *in press*).

Moreover, spatial anomalies in developmental dyslexia could reflect the consequences of having limited reading skill or experience. This assumption is supported by first results of an ongoing TVA-based study on developmental dyslexia suggesting that a spatial bias has not yet evolved in children in the third and fourth grade (Egetemeir, Finke, & Stenneken, 2011). However, to specify this issue, further direct comparisons of parametric values in children and adult dyslexics will be needed. In addition, more specific results concerning written language skills could be provided by future studies, taking the spatial processing of different letter positions in horizontal letter strings into account (in developmental dyslexia: e.g., Legge et al., 2007; in acquired forms of dyslexia: e.g., Montant, Nazir, & Poncet, 1998; Weinzierl, Kerkhoff, & Stenneken, 2009) and combine these with a TVA-based approach.

Taken together, the present findings suggest that the parameter w_λ might be indicative of the degree of changes in parietal asymmetry in reading disorders and, thus, may contribute to clinical appearance and the severity of the dyslexic disorder as well.

4.3. Limitations

The present study examined young adults with persisting dyslexia who had achieved an above-average academic level. Given this sample, on the one hand, a positive selection concerning the severity of the deficit must be assumed (favouring high-achieving, socially integrated persons), which might limit the generalizability of results. On the other hand, the selection of the present sample of adult participants allows us to investigate persisting deficits of high relevance that remained into adulthood. Future research will have to strengthen the database of parametric investigations, in order to specify possible effects of developmental change and influences of compensation or symptom remission in dyslexia. Parametric estimates from dyslexic children are available so far from two single cases (Dubois et al., 2010) and own ongoing research in a group study (Egetemeir et al., 2011), confirming the slowed perceptual processing in developmental dyslexia.

An additional, currently unresolved question concerns the material-specificity of the multi-element processing deficit in developmental dyslexia. Previous studies have revealed ambiguous results as to whether the impairment differentially affects only nameable units (such as symbols, digits or letters) or also other visual stimuli that are not associated with a phonological code.

Some studies have found no difference between developmental dyslexics and unimpaired readers in the processing of symbols (e.g., Hawelka & Wimmer, 2008; Ziegler et al., 2010), while others have reported that dyslexics perform worse than normal readers on symbol string tasks (Romani et al., 2011) and that low performance in these tasks is additionally associated with a higher number of reading errors (Pammer et al., 2004). Obviously, using objects such as letter stimuli involves additional processing (i.e., activation of the phonological code, even if no overt naming response is required) which might interfere with the processing strategy of multiple elements. Importantly, multi-element processing deficits have been reported in dyslexics even when controls were matched on reading level to the dyslexic group (Bosse & Valdois, 2003), a finding which substantially weakens the supposed relevance of phonological code activation in this type of task. Recent studies have confirmed the dyslexic multi-element processing deficit in methodologically elaborate investigations controlling for potential impairments in the processing of letter identities or phonological skills (De Luca et al., 2010; Romani et al., 2011).

Even though the present study did not aim to contribute to the question of material specificity, disturbances in letter naming (which can be ruled out according to the high educational level and pretest performance of the dyslexic participants) are unlikely to be causal for the marked and specific impairment of the perceptual processing speed observed in the dyslexic group. Rather, as has been argued, a global speed-of-processing impairment may also bring about disturbed naming performance or reduced naming fluency in developmental dyslexia (Jones, Branigan, Hatzidaki, & Obregón, 2010). On this view, the dyslexic symptoms would reflect a generalized difficulty in accessing information from multiple visual stimuli.

4.4. Clinical implications of the observed pattern of dyslexic deficits

In summary, the present study demonstrated a pattern of non-spatial processing speed deficits and spatial selectivity anomalies in developmental dyslexics. Such a combination of slow information uptake and spatial deviation in visual attention has been reported in previous TVA-studies for other patient groups patients with presumed hypoarousal of the right parietal alertness network and/or affecting temporoparietal areas (e.g., Bublak et al., 2005; Bublak, Redel, and Finke, 2006; Duncan et al., 1999; Robertson et al., 1998; Thimm, Fink, Küst, Karbe, & Sturm, 2006). Thus, the results of our dyslexic group indicate a pattern of deficits, which is characteristic for a low-alertness state of the brain or parietal dysfunction (cf., Finke et al., 2010).

The main finding of the present investigation with specific clinical interest is the marked reduction in processing speed. Significant deviations in this parameter could even be demonstrated in high-achieving adult dyslexics who had a clearly above-average academic educational level. A recent study (Lindgrén & Laine, 2011) of high-performing adult dyslexics (university students like in the present study) confirmed that deficits even in compensated dyslexia regarded not only higher-order written language skills, but were evident in different speed-related measures. These results support the sensitivity of the processing speed parameter for clinical assessment of compensated developmental dyslexia. The finding of a perceptual slowing can account for the repeatedly observed impairments in multi-element processing and might have predictive value for diagnosis and treatment of dyslexic impairments persisting into adulthood.

In the present study, comparative group analyses permitted to identify possible candidates of dysfunction, contributing to the clinical heterogeneity and cognitive complexity of a multi-system deficit like developmental dyslexia. The fine-grained parametric

assessment applying the TVA framework has proven a sensitive tool for both specifying and quantifying the cognitive functioning underlying persisting and even milder forms of developmental dyslexia by mathematically independent estimates within a unified framework.

Acknowledgements

We wish to thank Veronika Tanner and Petra Redel for support with data collection and analyses.

This work was supported in part by DFG, Center of Excellence 277 'Cognitive Interaction Technology', CITEC (P.St.).

Appendix A. Demographic and performance data of the dyslexic participants

Participant	Demographic and clinical data						TVA parameter estimates		
	Age (years)	Sex	Education (years of schooling)	Spelling score ^a	Pseudo word reading ^b	Word reading ^b	C	K	w _λ
KM	23	F	12	41	29.25	91.57	18.30	2.74	0.57
NH	25	M	13	40	42.57	86.50	17.20	3.62	0.51
TF	27	M	13	40	32.35	67.66	21.56	3.49	0.50
CR	27	F	13	29	37.31	76.65	35.53	5.00	0.42
JW	21	F	13	37	34.68	54.73	37.28	3.43	0.51
FB	19	M	12	24	38.37	85.82	21.18	2.80	0.49
VP	19	F	12	34	28.68	79.86	21.53	2.63	0.54
DN	19	M	12	25	35.56	77.40	19.64	3.78	0.50
VH	36	M	13	39	37.22	100.14	11.32	3.00	0.45
SL	24	M	11	30	25.75	71.10	17.15	3.92	0.47
BH	27	M	13	40	41.30	96.00	31.67	3.61	0.46
SH	26	F	13	42	63.46	107.64	19.68	3.61	0.50
MA	23	M	13	34	38.25	72.67	14.41	3.83	0.50
KS	23	F	13	45	57.35	97.50	19.24	3.41	0.51
DH	30	M	13	30	27.40	54.36	13.07	2.83	0.48
BB	22	F	13	42	37.99	81.24	19.86	3.50	0.56
KK	21	F	13	40	29.89	62.74	14.36	3.92	0.49
RB	26	M	13	37	27.13	85.38	20.34	3.43	0.52
RL	27	F	13	42	50.26	98.35	14.90	2.94	0.56
YF	34	F	13	25	42.06	89.62	11.95	2.96	0.46
TL	22	M	10	26	60.60	114.00	12.11	3.00	0.46
AF	23	F	13	32	41.38	99.33	14.71	4.00	0.43
MG	28	M	13	47	48.74	103.00	13.59	3.47	0.57

^a T-scores of spelling test (Rechtschreibungstest, Kersting & Althoff, 2004).

^b Composite reading score: Number of correctly read items per minute, each averaged over results in both reading lists (Word and Pseudoword Reading List, Schulte-Körne, 2001; 1-Minute Reading Fluency Test, Willburger & Landerl, 2009).

References

- Averbach, E., & Sperling, G. (1968). Short term storage of information in vision. In R. N. Haber (Ed.), *Contemporary theory and research in visual perception* (pp. 196–211). New York: Holt, Rinehart and Winston.
- American Psychiatric Association. (2000). *Diagnostic and statistical manual of mental disorders* (4th ed.). Washington, DC: American Psychiatric Association.
- Bosse, M. L., Tainturier, M. J., & Valdois, S. (2007). Developmental dyslexia: The visual attention span deficit hypothesis. *Cognition*, *104*(2), 198–230.
- Bosse, M. L., & Valdois, S. (2003). Patterns of developmental dyslexia according to a multi-trace memory model of reading. *Current Psychology Letters*, *10*(1), 2–8.
- Bowers, D., & Heilman, K. M. (1980). Pseudoneglect: Effects of hemispace on a tactile line bisection task. *Neuropsychologia*, *18*(4–5), 491–498.
- Braet, W., & Humphreys, G. (2007). A selective effect of parietal damage on letter identification in mixed case words. *Neuropsychologia*, *45*(10), 2226–2233.
- Bublak, P., Finke, K., Krummenacher, J., Preger, R., Kyllingsbæk, S., Müller, H. J., et al. (2005). Usability of a theory of visual attention (TVA) for parameter-based measurement of attention II: Evidence from two patients with frontal or parietal damage. *Journal of the International Neuropsychological Society*, *11*(7), 843–854.
- Bublak, P., Redel, P., & Finke, K. (2006). Spatial and non-spatial attention deficits in neurodegenerative diseases: Assessment based on Bundesen's theory of visual attention (TVA). *Restorative Neurology and Neuroscience*, *24*(4–6), 287–301.
- Buchholz, J., & Davies, A. A. (2005). Adults with dyslexia demonstrate space-based and object-based covert attention deficits: Shifting attention to the periphery and shifting attention between objects in the left visual field. *Brain and Cognition*, *57*(1), 30–34.
- Bundesen, C. (1990). A theory of visual attention. *Psychological Review*, *97*(4), 523–547.
- Bundesen, C. (1998). A computational theory of visual attention. *Philosophical Transactions of the Royal Society of London B*, *353*(1373), 1271–1281.
- Bundesen, C., Habekost, T., & Kyllingsbæk, S. (2005). A neural theory of visual attention: Bridging cognition and neurophysiology. *Psychological Review*, *112*(2), 291–328.
- Cestnick, L., & Coltheart, M. (1999). The relationship between language-processing and visual-processing deficits in developmental dyslexia. *Cognition*, *71*(3), 231–255.
- Conners, K., Erhardt, D., & Sparrow, E. P. (1999). *CAARS Conners' Adult ADHD Rating Scales*. New York: Multi-Health Systems.
- De Luca, M., Burani, C., Paizi, D., Spinelli, D., & Zoccolotti, P. (2010). Letter and letter-string processing in developmental dyslexia. *Cortex*, *46*, 1272–1283.
- Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience*, *18*, 193–222.
- Di Lollo, V. (1980). Temporal integration in visual memory. *Journal of Experimental Psychology: General*, *109*, 75–97.
- Di Pellegrino, G., Ládavas, E., & Galletti, C. (2002). Lexical processes and eye movements in neglect dyslexia. *Behavioural Neurology*, *13*(1–2), 61–74.
- Dubois, M., Kyllingsbæk, S., Prado, C., Musca, S. C., Peiffer, E., Lassus-Sangosse, D., et al. (2010). Fractionating the multi-character processing deficit in developmental dyslexia: Evidence from two case studies. *Cortex*, *46*(6), 717–738.
- Duncan, J., Bundesen, C., Olson, A., Humphreys, G., Chavda, S., & Shibuya, H. (1999). Systematic analysis of deficits in visual attention. *Journal of Experimental Psychology: General*, *128*(4), 450–478.
- Duncan, J., Bundesen, C., Olson, A., Humphreys, G., Ward, R., Kyllingsbæk, S., et al. (2003). Attentional functions in dorsal and ventral simultanagnosia. *Cognitive Neuropsychology*, *20*(8), 675–701.
- Egetemeir, J., Finke, K., & Stenken, P. (2011). Visual attention and developmental dyslexia. Parameter-based assessment of disordered and intact components of visual attention. Cognitive Neuroscience Society—2011 Annual Meeting. *Supplement of the Journal of Cognitive Neuroscience*, 84.
- Facoetti, A., Lorusso, M. L., Paganoni, P., Cattaneo, C., Galli, R., Umiltà, C., et al. (2003). Auditory and visual automatic attention deficits in developmental dyslexia. *Cognitive Brain Research*, *16*(2), 185–191.
- Facoetti, A., & Molteni, M. (2001). The gradient of visual attention in developmental dyslexia. *Neuropsychologia*, *39*, 352–357.
- Facoetti, A., & Turatta, M. (2000). Asymmetrical visual field distribution of attention in dyslexic children: A neuropsychological study. *Neuroscience Letters*, *290*, 216–218.
- Facoetti, A., Zorzi, M., Cestnick, L., Lorusso, M. L., Molteni, M., Paganoni, P., et al. (2006). The relationship between visuo-spatial attention and nonword reading in developmental dyslexia. *Cognitive Neuropsychology*, *23*(6), 841–855.
- Finke, K., Bublak, P., Dose, M., Müller, H. J., & Schneider, W. X. (2006). Parameter-based assessment of spatial and non-spatial attentional deficits in Huntington's disease. *Brain*, *129*(5), 1137–1151.
- Finke, K., Bublak, P., Krummenacher, J., Kyllingsbæk, S., Müller, H. J., & Schneider, W. X. (2005). Usability of a theory of visual attention (TVA) for parameter-based measurement of attention I: Evidence from normal subjects. *Journal of the International Neuropsychological Society*, *11*(7), 832–842.
- Finke, K., Bublak, P., & Zihl, J. (2006). Visual spatial and visual pattern working memory: Neuropsychological evidence for a differential role of left and right dorsal visual brain. *Neuropsychologia*, *44*(4), 649–661.
- Finke, K., Dodds, C., Bublak, P., Regenthal, R., Baumann, F., Manly, T., et al. (2010). Effects of modafinil and methylphenidate on visual attention capacity: A TVA-based study. *Psychopharmacology*, *210*(3), 317–329.
- Finke, K., Schwarzkopf, W., Müller, U., Frodt, T., Müller, H. J., Schneider, W. X., et al. Disentangling the adult attention-deficit hyperactivity disorder endophenotype: Parametric measurement of attention. *Journal of Abnormal Psychology*, Aug 22. [Epub ahead of print], PMID: 21859167, in press.
- Geiger, G., Jerome, Y. L., & Zegarra-Moran, O. (1992). Task-determined strategies of visual process. *Cognitive Brain Research*, *1*(1), 39–52.
- Habekost, T., & Bundesen, C. (2003). Patient assessment based on a theory of visual attention (TVA): Subtle deficits after a right frontal-subcortical lesion. *Neuropsychologia*, *41*(9), 1171–1188.
- Habekost, T., & Rostrup, E. (2006). Persisting asymmetries of vision after right side lesions. *Neuropsychologia*, *44*(6), 876–895.
- Habekost, T., & Starrfelt, R. (2009). Visual attention capacity: A review of TVA-based patient studies. *Scandinavian Journal of Psychology*, *50*(1), 23–32.
- Habib, M. (2000). The neurological basis of developmental dyslexia. *Brain*, *123*, 2373–2399.
- Habib, M., & Robichon, F. (1996). Parietal lobe morphology predicts phonological skills in developmental dyslexia. *Brain and Cognition*, *32*(2), 139–142.
- Hari, R., Renvall, H., & Tanskanen, T. (2001). Left minineglect in dyslexic adults. *Brain*, *124*, 1373–1380.
- Hawelka, S., & Wimmer, H. (2005). Impaired visual processing of multi-element arrays is associated with increased number of eye movements in dyslexic reading. *Vision Research*, *45*(7), 855–863.
- Hawelka, S., & Wimmer, H. (2008). Visual target detection is not impaired in dyslexic readers. *Vision Research*, *48*(6), 850–852.
- Heim, S., Tschierse, J., Amunts, K., Wills, M., Vossel, S., Willmes, K., et al. (2008). Cognitive subtypes of dyslexia. *Acta Neurobiologiae Experimentalis*, *68*(1), 73–82.
- Hoefl, F., Meyler, A., Hernandez, A., Juel, C., Taylor-Hill, H., Martindale, J. L., et al. (2007). Functional and morphometric brain dissociation between dyslexia and reading ability. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(10), 4234–4239.
- Husain, M., & Rorden, C. (2003). Non-spatially lateralized mechanisms in hemispatial neglect. *Nature Reviews Neuroscience*, *4*, 26–36.
- Jewell, G., & McCourt, M. E. (2000). Pseudoneglect: A review and meta-analysis of performance factors in line bisection tasks. *Neuropsychologia*, *38*(1), 93–110.
- Jones, M. W., Branigan, H. P., Hatzidakis, A., & Obregón, M. (2010). Is the 'naming' deficit in dyslexia a misnomer? *Cognition*, *116*(1), 56–70.

- Jones, M. W., Branigan, H. P., & Kelly, M. L. (2008). Visual deficits in developmental dyslexia: Relationships between non-linguistic visual tasks and their contribution to components of reading. *Dyslexia*, 14(2), 95–115.
- Kail, R., & Hall, L. K. (1994). Processing speed, naming speed, and reading. *Developmental Psychology*, 30(6), 949–954.
- Kerkhoff, G. (2001). Spatial hemineglect in humans. *Progress in Neurobiology*, 63, 1–27.
- Kersting, M., & Althoff, K. (2004). *Rechtschreibungstest RT [Spelling test]*. Göttingen: Hogrefe.
- Kinsbourne, M., & Warrington, E. K. (1962). A disorder of simultaneous form perception. *Brain*, 85, 461–486.
- Kyllingsbæk, S. (2006). Modeling visual attention. *Behavior Research Methods*, 38, 123–133.
- Landerl, K., Wimmer, H., & Frith, U. (1997). The impact of orthographic consistency on dyslexia: A German-English comparison. *Cognition*, 63(3), 315–334.
- Legge, G. E., Cheung, S.-H., Yu, D., Chung, S. T. L., Lee, H.-W., & Owens, D. P. (2007). The case for the visual span as a sensory bottleneck in reading. *Journal of Vision*, 7(2), 9.1–15.
- Lehrl, S. (1999). *MWT-B Mehrfachwahl-Wortschatz-Intelligenztest [Multiple choice vocabulary test]*. Balingen: Spitta.
- Liddle, E. B., Jackson, G. M., Rorden, C., & Jackson, S. R. (2009). Lateralized temporal order judgement in dyslexia. *Neuropsychologia*, 47, 3244–3254.
- Lindgrén, S. A., & Laine, M. (2011). Cognitive-linguistic performances of multilingual university students suspected of dyslexia. *Dyslexia*, 17(2), 184–200.
- Ludwig, K. U., Roeske, D., Herms, S., Schumacher, J., Warnke, A., Plume, E., et al. (2009). Variation in GRIN2B contributes to weak performance in verbal short-term memory in children with dyslexia. *American Journal of Medical Genetics Part B: Neuropsychiatric Genetics*, 153(2), 503–511.
- Matthias, E., Bublak, P., Costa, A., Müller, H. J., Schneider, W. X., & Finke, K. (2009). Attentional and sensory effects of lowered levels of intrinsic alertness. *Neuropsychologia*, 47(14), 3255–3264.
- Matthias, E., Bublak, P., Müller, H. J., Schneider, W. X., Krummenacher, J., & Finke, K. (2010). The influence of alertness on spatial and nonspatial components of visual attention. *Journal of Experimental Psychology: Human Perception and Performance*, 36(1), 38–56.
- McCandliss, B. D., & Noble, K. G. (2003). The development of reading impairment: A cognitive neuroscience model. *Mental Retardation and Developmental Disability Research Reviews*, 9(3), 196–205.
- Menghini, D., Finzi, A., Benassi, M., Bolzani, R., Facoetti, A., Giovagnoli, S., et al. (2010). Different underlying neurocognitive deficits in developmental dyslexia: A comparative study. *Neuropsychologia*, 48(4), 863–872.
- Montant, M., Nazir, T., & Poncet, M. (1998). Pure alexia and the viewing position effect in printed words. *Cognitive Neuropsychology*, 15, 93–140.
- Morris, R. D., Stuebing, K. K., Fletcher, J. M., Shaywitz, S. E., Lyon, G. R., Shankweiler, D. P., et al. (1998). Subtypes of reading disability: Variability around a phonological core. *Journal of Educational Psychology*, 90(3), 347–373.
- Pammer, K., Lavis, R., Hansen, P., & Cornelissen, P. L. (2004). Symbol-string sensitivity and children's reading. *Brain and Language*, 89(3), 601–610.
- Peers, P. V., Ludwig, C. J. H., Rorden, C., Cusack, R., Bonfiglioli, C., Bundesen, C., et al. (2005). Attentional functions of parietal and frontal cortex. *Cerebral Cortex*, 15(10), 1469–1484.
- Peyrin, C., Démonet, J. F., N'Guyen-Morel, M. A., Le Bas, J. F., & Valdois, S. (2011). Superior parietal lobule dysfunction in a homogeneous group of dyslexic children with a visual attention span disorder. *Brain and Language*, 118(3), 128–138.
- Prado, C., Dubois, M., & Valdois, S. (2007). The eye movements of dyslexic children during reading and visual search: Impact of the visual attention span. *Vision Research*, 47(19), 2521–2530.
- Ramus, F., Rosen, S., Dakin, S. C., Day, B. L., Castellote, J. M., White, S., et al. (2003). Theories of developmental dyslexia: Insights from a multiple case study of dyslexic adults. *Brain*, 126(4), 841–865.
- Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, 124(3), 372–422.
- Redel, P., Bublak, P., Sorg, C., Kurz, A., Förstl, H., Müller, H. J., et al. Deficits of spatial and task-related attentional selection in mild cognitive impairment and Alzheimer's disease. *Neurobiology of Aging*, pii:S0197-4580(10)00228-9, doi:10.1016/j.neurobiolaging.2010.05.014, in press.
- Rimrodt, S. L., Peterson, D. J., Denckla, M. B., Kaufmann, W. E., & Cutting, L. E. (2010). White matter microstructural differences linked to left perisylvian language network in children with dyslexia. *Cortex*, 46(6), 739–749.
- Robertson, I. H., Mattingley, J., Rorden, C., & Driver, J. (1998). Phasic alerting of neglect patients overcomes their spatial deficit in visual awareness. *Nature*, 395, 169–172.
- Romani, C., Tsouknida, E., di Betta, A. M., & Olson, A. (2011). Reduced attentional capacity, but normal processing speed and shifting of attention in developmental dyslexia: Evidence from a serial task. *Cortex*, 47, 715–733.
- Ross, S. M. (2000). *Introduction to probability and statistics for engineers and scientists*. San Diego: Academic Press.
- Ruffino, M., Trussardi, A. N., Gori, S., Finzi, A., Giovagnoli, S., Menghini, D., et al. (2010). Attentional engagement deficits in dyslexic children. *Neuropsychologia*, 48, 3793–3801.
- Scerri, T. S., & Schulte-Körne, G. (2010). Genetics of developmental dyslexia. *European Child & Adolescent Psychiatry*, 19(3), 179–197.
- Schulte-Körne, G. (2001). *Lese-Rechtschreibstörung und Sprachwahrnehmung: Psychometrische und neurophysiologische Untersuchungen zur Legasthenie [Dyslexia and speech perception]*. Pädagogische Psychologie und Entwicklungspsychologie. Münster: Waxmann.
- Schulte-Körne, G., Bartling, J., Deimel, W., & Remschmidt, H. (2004). Visual evoked potentials elicited by coherently moving dots in dyslexic children. *Neuroscience Letters*, 357(3), 207–210.
- Schulte-Körne, G., & Bruder, J. (2010). Clinical neurophysiology of visual and auditory processing in dyslexia: A review. *Clinical Neurophysiology*, 121(11), 1794–1809.
- Shalev, L., Mevorach, C., & Humphreys, G. W. (2008). Letter position coding in attentional dyslexia. *Neuropsychologia*, 46(8), 2145–2151.
- Shaywitz, S. E., Shaywitz, B. A., Pugh, K. R., Fulbright, R. K., Constable, R. T., Mencl, W. E., et al. (1998). Functional disruption in the organization of the brain for reading in dyslexia. *Proceedings of the National Academy of Sciences of the United States of America*, 95(5), 2636–2641.
- Sireteanu, R., Goertz, R., Bachert, I., & Wandert, T. (2005). Children with developmental dyslexia show a left visual minineglect. *Vision Research*, 45(25–26), 3075–3082.
- Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs*, 74, 11–20.
- Starrfelt, R., Habekost, T., & Gerlach, C. (2010). Visual processing in pure alexia: A case study. *Cortex*, 46(2), 242–255.
- Starrfelt, R., Habekost, T., & Leff, A. P. (2009). Too little, too late: Reduced visual span and speed characterize pure alexia. *Cerebral Cortex*, 19(12), 2880–2890.
- Stenneken, P., van Eimeren, L., Jacobs, A. M., Keller, I., & Kerkhoff, G. (2008). Task-dependent modulation of neglect dyslexia? Novel evidence from the viewing position effect. *Brain Research*, 1189(16), 166–178.
- Thimm, M., Fink, G. R., Küst, J., Karbe, H., & Sturm, W. (2006). Impact of alertness training on spatial neglect: A behavioural and fMRI study. *Neuropsychologia*, 44(7), 1230–1246.
- Valdois, S., Bosse, M. L., Ans, B., Carbonnel, S., Zorman, M., David, D., et al. (2003). Phonological and visual processing deficits can dissociate in developmental dyslexia: Evidence from two case studies. *Reading and Writing*, 16, 541–572.
- Valdois, S., Bosse, M. L., & Tainturier, M. J. (2004). The cognitive deficits responsible for developmental dyslexia: Review of evidence for a selective visual attentional disorder. *Dyslexia*, 10(4), 1–25.
- Vangkilde, S., Bundesen, C., & Coull, J. T. Prompt but inefficient: Nicotine differentially modulates discrete components of attention. *Psychopharmacology*, doi:10.1007/s00213-011-2361-x, in press.
- Waldie, K. E., & Hausmann, M. (2010). Right fronto-parietal dysfunction in children with ADHD and developmental dyslexia as determined by line bisection judgements. *Neuropsychologia*, 48(12), 3650–3656.
- Weinzierl, C., Kerkhoff, G., & Stenneken, P. (2009). Analyse von Lesefehlern bei Neglectdyslexie: Fehlertypen und Fehlerpositionen bei der Wortbenennung [Analysis of reading errors in neglect dyslexia: Error types and error positions in word naming]. In A. B. Eder, K. Rothermund, S. R. Schweinberger, M. C. Steffens, & H. Wiese (Eds.), *Abstracts der 51. Tagung experimentell arbeitender Psycholog/innen [Abstracts of the 51th conference of experimental psychologists]* (p. 123). Lengerich: Pabst.
- Weiß, R. H. (1998). *CFT 20 Grundintelligenztest Skala 2 [Culture Fair Intelligence Test, Scale 2, German adaptation]*. Göttingen: Hogrefe.
- White, S., Milne, E., Rosen, S., Hansen, P., Swettenham, J., Frith, U., et al. (2006). The role of sensorimotor impairments in dyslexia: A multiple case study of dyslexic children. *Developmental Science*, 9(3), 237–269.
- Whitney, C., & Cornelissen, P. (2005). Letter-position encoding and dyslexia. *Journal of Research in Reading*, 28(3), 274–301.
- Willburger, E., & Landerl, K. (2009). Der Ein-Minuten Leseflüssigkeitstest—ein Verfahren zur Diagnose der Leistung im Wort- und Pseudowortlesen [1-Minute Reading Fluency Test]. In W. Lenhard, & W. Schneider (Eds.), *Tests und Trends: Vol. 7. Diagnostik und Förderung des Leseverständnisses* (pp. 65–80). Göttingen: Hogrefe.
- Wimmer, H. (1993). Characteristics of developmental dyslexia in a regular writing system. *Applied Psycholinguistics*, 14(1), 1–33.
- World Health Organization. (2007). *International statistical classification of diseases and related health problems* (10th ed.). Geneva: World Health Organization.
- Ziegler, J. C., Pech-Georgel, C., Dufau, S., & Grainger, J. (2010). Rapid processing of letters digits and symbols: What purely visual-attentional deficit in developmental dyslexia? *Developmental Science*, 13(4), F8–F14.