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PRE-ORTHOGRAPHICAL CONSTRAINTS IN READING AND MULTI-ELEMENT PROCESSING IN DYSLEXIA

Evidence from single case studies and data modelling

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Jury

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Abstract

The present thesis was concerned with the possible constraints set by visual and attentional pre-orthographical factors on visual word recognition in dyslexic individuals.

In a first study, we investigated the visual word recognition ability of MT, a young boy with surface dyslexia, by means of a paradigm that measures performance as a function of the eye fixation position within the word, known as the “viewing position effect” paradigm. In well-achieving readers, the viewing position effect is mainly determined by factors affecting letter visibility and by lexical constraints on word recognition. We further quantified MT’s sensory limitations on letter visibility by computing visual span profiles, i.e. the number of letters recognizable at a glance. Finally, in an ideal-observer’s perspective, MT’s performance was compared with a parameter-free model combining MT’s letter visibility data with a simple lexical matching rule. The results showed that MT did not use the whole visual information available on letter identities to recognise words. These results can be best accounted for by a reduction of the number of letters processed in parallel.

Accordingly, there is growing evidence that some dyslexic children suffer from a deficit in simultaneously processing of multiple visually displayed elements. The aim of the remaining studies was to investigate possible cognitive impairments at the source of the multi-element visual processing deficit in dyslexic children. A computational model of the attentional involvement in multi-object recognition [TVA: Bundesen, C. (1990). A theory of visual attention. *Psychological Review*, 97(4), 523–47] served as framework for this investigation. In a second study, we used TVA to investigate multi-element processing in two young dyslexic participants, AB and PA. By combining psychophysical measurements with computational modelling, we demonstrated that this multi-element processing deficit stems from two distinct cognitive sources: a reduction of the rate of visual information uptake, and a limitation of the visual short-term memory capacity. These deficits were replicated in a third study, in which the multi-element processing was investigated in three dyslexic individuals, FA, LT and YC. The last study further demonstrated that the multi-element processing deficit observed in dyslexia is not simply due to a sluggish activation of items names, instead of visual processing difficulties. Finally, the generalisability of the multi-element processing deficit has been assessed by comparing report performance of letters vs colour patches. Unfortunately, the results were inconclusive.

Taken together, the results of these different studies point to a reduced capacity of processing visual information in parallel (at least for letters), that might constrain visual word recognition.

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Foreword

Developmental dyslexia, i.e. an impairment of normal reading acquisition, is one of the most common specific learning disabilities. This disorder affects between 5% and 15% of the population of school-age children (e.g. [Katusic, Colligan, Barbaresi, Schaid, & Jacobsen, 2001](#); [Shaywitz, Shaywitz, Fletcher, & Escobar, 1990](#)). The question of why some children have difficulty learning to read has been the focus of a great deal of research over the past four decades. The proposal of a phonological deficit as the cognitive basis of developmental dyslexia is now widely accepted (for reviews, see [Shaywitz & Shaywitz, 2005](#); [Vellutino, Fletcher, Snowling, & Scanlon, 2004](#)). The phonological theory is grounded in the fact that reading is an oral language activity, which consists of orally producing printed words. Unfortunately, the current emphasis on a phonological deficit in dyslexia has overshadowed the fact that reading is also a visual task.

That dyslexia may be related to visual defects has regularly been proposed throughout more than a century of research. The term ‘congenital word-blindness’ was proposed by [Morgan](#) in 1896 to describe the first reported case of developmental dyslexia. However, the hypothesis of a visual defect as a possible source of dyslexia has been seriously challenged by the work of [Vellutino \(1979\)](#), which contested the presence of visual impairments in dyslexic children and strongly established its phonological origin. Current interest for the visual function in dyslexic individuals restarted with a study by [Livingstone, Rosen, Drislane, and Galaburda](#). In 1991, they demonstrated anatomical abnormalities in specific layers of a nucleus of the thalamus, the lateral geniculate nucleus, a sub-cortical visual relay between the retina and the primary visual cortex. Since then, the integrity of the sub-cortical and cortical visual pathways (including visual attention mechanisms) were repeatedly investigated. Specific visual and attentional deficiencies were congruently reported in individuals with dyslexia (for a review, see e.g. [Stein, 2003](#)). This raises an important question: do visual or attentional factors constrain visual word recognition in dyslexic children? The answer is not

obvious, as made clear by a recent review of the literature assessing the plausibility of different possible hypotheses (Boden & Giaschi, 2007). Most proposed hypotheses are currently largely speculative and critical evidence for a causal relation is lacking. These topics are developed in Chapter 1.

One of the main difficulties in bridging the gap between visual and attentional functions on one hand, and reading acquisition on the other hand, may stem from the fact that visual and attentional functions are generally investigated for their own, and not in connection to reading mechanisms. The purpose of this Ph.D. thesis is to make a first step in bridging this gap, by investigating some visual and attentional pre-orthographical factors that might constrain visual word recognition in dyslexic individuals. This topic received interest only very recently, and most investigations are contemporary to the researches reported in this dissertation. For the sake of clarity, the current state of the literature is nevertheless presented in Chapter 2.

My interest for pre-orthographical constraints in visual word recognition in fact originates in the single case study of a young French-speaking dyslexic boy, MT. This single case is reported in Chapter 4. He demonstrated a strong reading and writing impairment, despite normal or above normal phonological skills. The absence of a phonological deficit, in conjunction with the production of visual errors in reading, led us to explore in greater detail MT's pre-orthographical processing in single word recognition. The confrontation of MT's behavioural data with a simple visual model achieving visual word recognition strongly suggested that MT did not use the whole available visual information on letter identities to recognise words. These results were in line with a recent proposal that some dyslexic individuals might suffer from a reduction of the number of visual elements simultaneously processed (Bosse, Tainturier, & Valdois, 2007; Valdois et al., 2003).

The subsequent studies aimed at determining the precise nature of the cognitive impairments at the source of this multi-element processing deficit in dyslexic children, in a parameter-based fashion. In Chapter 5, we used a formal model of visual attention and (multi-) object recognition: the Theory of Visual Attention (Bundesen, 1990, 1998; Bundesen, Habekost, & Kyllingsbæk, 2005) in order to fractionate multi-element processing performance into theoretically meaningful components. This model formalises interactions between vision, visual attention, and object recognition (letter recognition, in the current case). By combining psychophysical measurements in a letter report task with computational modelling, we demonstrated that the multi-element processing deficit in dyslexia stems from at least two distinct cognitive sources, both related

to capacity limits of information processing. These results are reported in Chapter 5. Results were replicated and extended in a third study, described in Chapter 6. This last study also addresses additional questions, such as the possible impact of the oral report procedure we used to measure letter recognition. It further attempted to investigate whether the multi-element processing extended to other material than letters or letter-like symbols.

Part I

Theoretical context

Chapter 1

About dyslexia

In this introductory chapter, we will provide the reader with a quick overview on what is dyslexia (at least in orthographical written systems) and what are the major theoretical frameworks that have been proposed to account for it. Most of the content of this chapter was directly inspired by a extensive review of the literature recently published by the French [Institut National de la Santé et de la Recherche Médicale \(2007\)](#). French-speaking readers are directed to this publication for more details on developmental dyslexia.

1.1 Defining dyslexia

Various definitions of dyslexia have been provided. Moreover, the notion of dyslexia has evolved throughout time, following scientific knowledge.

Following the International Classification of Diseases (ICD-10: [Organisation Mondiale de la Santé, 1994](#), code F81.0), the main feature of dyslexia (specific reading disorder) is “a specific and significant impairment in the development of reading skills that is not solely accounted for by mental age, visual acuity problems, or inadequate schooling. Reading comprehension skill, reading word recognition, oral reading skill, and performance of tasks requiring reading may all be affected. Spelling difficulties are frequently associated with specific reading disorder and often remain into adolescence even after some progress in reading has been made. Specific developmental disorders are commonly preceded by a history of disorders in speech or language development. Associated emotional and behavioural disturbances are common during the school age period.” This definition includes the criteria classically used for an operational definition of dyslexia: (i) a *discrepancy* criterion between significant difficulties observed on reading tasks and the expected level

in function of chronological age and intellectual achievement (IQ). Following the ICD-10, a discrepancy of at least two standard-deviations is required; (ii) an *exclusion* criterion: the reading deficiencies observed may be primarily caused neither by a general mental or intellectual retardation, nor by a basic sensory or gross neurological impairment. Also, the child must have been provided with a sufficiently favourable socio-cultural and educational environment. Similar criteria were used in the operational definition of dyslexia proposed in the diagnostic and statistical manual of mental disorders (DSM), published by the [American Psychiatric Association \(1994\)](#). Finally, most definitions further emphasise the neurobiological origin of the reading deficiency (e.g. [Démonet, Taylor, & Chaix, 2004](#); [Habib, 2000](#)).

The discrepancy criterion has lead to distinguish between low-IQ poor readers, in which no discrepancy was observed between reading abilities and intellectual performance, and dyslexic children, in which a reading impairment is observed despite a normal IQ. However, the relevance of this criterion has largely been questioned. Indeed, low- and high-IQ poor readers show similar reading and reading-related skills impairments patterns and benefit from the same remediation programs (for a review, see [Stanovich, 2005](#)). This criterion nevertheless remains largely used for dyslexic participants' selection.

Most recent definitions of dyslexia further refer to the cognitive mechanisms that are deficient in dyslexic people and the aetiology of these troubles ([Shaywitz & Shaywitz, 2005](#)). This is best exemplified in the definition proposed by [Lyon, Shaywitz, and Shaywitz \(2003, p. 2\)](#): “Dyslexia is a specific learning disability that is neurobiological in origin. It is characterised by difficulties with accurate and/or fluent word recognition and by poor spelling and decoding abilities. *These difficulties typically result from a deficit in the phonological component of language*¹ that is often unexpected in relation to other cognitive abilities and the provision of effective classroom instruction. Secondary consequences may include problems in reading comprehension and reduced reading experience that can impede growth of vocabulary and background knowledge.” However, such definitions are not without problem. There is indeed a large amount of evidence that phonology plays an important role in learning to read and that dyslexia is often accompanied by a phonological trouble. This has lead some authors to propose a unique core phonological deficit at the source of dyslexia (see [Section 1.3](#)). However, this hypothesis has been challenged by the widely admitted heterogeneity of the dyslexic population, and by several reports of dyslexic individuals

¹I emphasised in the text.

with no apparent phonological deficit (for a review, see [Valdois, Bosse, & Tainturier, 2004](#)). Evidence was also reported in favour of other deficiencies potentially responsible for dyslexia (see Section 1.3, and Chapter 2). Moreover, the recent investigation of cognitive and genetic bases of the observed comorbidity between dyslexia and other troubles (such as attention deficit and hyperactivity disorder —ADHD— or specific language disorder —SLD—) has lead some researchers to propose multi-factorial accounts of dyslexia (e.g. [Pennington, 2006](#)). As a consequence, including a phonological deficit as a criterion for defining dyslexia remains at least controversial ([Coltheart & Jackson, 1998](#)).

1.2 Standard classification of reading problems in developmental dyslexia

Several subtypes of dyslexia have been described ([Boder, 1973](#); [Castles & Coltheart, 1993](#)). The most widely used sub-typing of developmental reading problems was initially derived from the dual-route models of expert reading ([Coltheart, 1978](#); [Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001](#); [Marshall & Newcombe, 1973](#)). The basic architecture of these models is outlined in Figure 1.1. As made clear in this figure, two distinct pathways are postulated in order to read an item. In the direct (or lexical) pathway, the item is processed globally through the activation of previously learned orthographical lexical word representations. This activation further spread to a phonological lexicon, either directly or through the access to the semantics associated to the word. On the contrary, in the indirect or sublexical pathway, the word to be read is decomposed into graphemes (the written code corresponding to a phoneme: a minimal distinctive sound of that language), and previously learned grapheme-to-phoneme conversion rules apply. In this framework, different types of items are preferentially processed by each of the two pathways. Accessing a lexical representation is required to accurately read irregular words. Indeed, applying regular grapheme-to-phoneme mapping rules would result in erroneous reading. Contrarily, the sub-lexical route is mainly dedicated to new words, for which no lexical representation exists. As a consequence, this sub-lexical pathway is mainly assessed by reading pseudo-words. Pseudo-words are meaningless sequences of letters in which orthographical and phonological rules of a given language are respected. Sub-types of dyslexia were thus classically defined by contrasting the reading performance on list of regular and irregular words, as well as matched pseudo-words. Subsequently, developmental analogues of the distinct sub-types observed in brain-

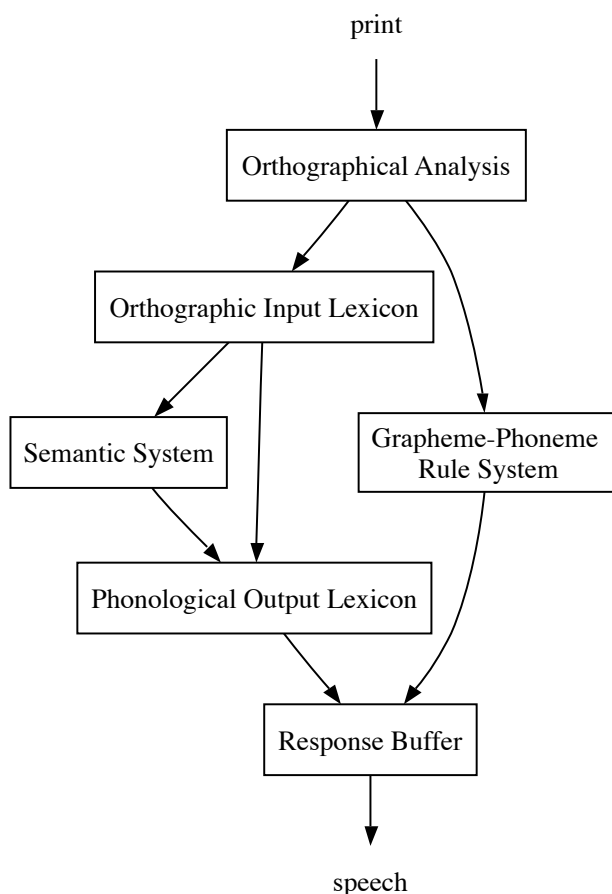


Figure 1.1: Basic architecture of the dual-route cascaded model of expert reading. Redrawn from [Coltheart and Davies \(2003\)](#).

damaged patients were described in dyslexic children. [Castles and Coltheart \(1993\)](#) proposed three different varieties: phonological, surface and mixed dyslexia. These varieties correspond to an impairment in one or both of the two pathways of the dual-route model. However, they have received other interpretations in other theoretical accounts of reading, in which all types of words are read according to the same computational principle (e.g. *parallel distributed processing* networks: [Harm & Seidenberg, 1999](#); [Plaut, McClelland, Seidenberg, & Patterson, 1996](#); [Seidenberg & McClelland, 1989](#); multi-trace memory network: [Ans et al., 1998](#)).

Phonological dyslexia is characterised by a selective difficulty in read-

ing pseudo-words, while reading regular and irregular words is relatively preserved. Lexicalisation errors are further observed, resulting in producing a visually similar word instead of the targeted pseudo-word. The pattern observed in spelling under dictation is similar to the one observed in reading: major difficulties in spelling pseudo-words, while the spelling of regular and irregular words is better preserved. Phonological dyslexia is related to the dysphonetic class proposed by Boder (1973). Numerous cases of developmental phonological dyslexia have been reported (e.g. Broom & Doctor, 1995a; Howard & Best, 1996; Valdois et al., 2003). All these cases further presented an associated deficit on metaphonological tasks. Moreover, when assessed, a verbal short-term memory impairment was often reported (but see Hanley & Gard, 1995). In metaphonological tasks, the participant had to explicitly manipulate linguistic units within spoken words or pseudo-words. An example of such tasks is the omission of the first phoneme of an orally given pseudo-word. The deficit observed in all described cases of phonological dyslexia on metaphonological tasks is strongly indicative of an underlying phonological deficit.

The reading pattern characteristic of surface dyslexia is symmetric to the one observed in phonological dyslexia. It grossly corresponds to the dyseidetic profile described by Boder (1973). The reading performance is selectively impaired for irregular words, while regular word as well as pseudo-word reading is better preserved. Moreover, regularisation errors are observed. They consist of erroneously pronouncing irregular words by applying the regular conversion rules. Visual confusions between visually similar letters are also reported. Surface dyslexia is classically associated with a massive dysorthographia, in which performance is mainly affected by word complexity. The same pattern of difficulties is thus observed in spelling as well as in reading. Also, numerous cases of developmental surface dyslexia were described (e.g. Broom & Doctor, 1995b; Brunson, Coltheart, & Nickels, 2005; Castles & Coltheart, 1996; Goulandris & Snowling, 1991; Samuelsson, 2000; Valdois, 1996; Valdois et al., 2003). The absence of any oral language impairment, as well as intact metaphonological skills and normal verbal short-term memory capacity, have been reported when they were estimated. However, the cases described in these studies were often adolescents or young adults. This rise the possibility that a phonological deficit was in fact present when beginning to read, but well compensated and thus not observed at the time of the study. The sensitivity of the phonological measures has also been questioned (e.g. Sprenger-Charolles, Colé, Lacert, & Serniclaes, 2000).

The difficulty to compare results from different studies and obtained with different tasks has been overcome by comparing contrasting closely

matched cases of phonological and surface dyslexia. [Valdois et al. \(2003\)](#) contrasted the profiles of two age- and reading-level matched young dyslexic children, one showing a reading pattern characteristic of phonological dyslexia, the other of surface dyslexia. While the phonological dyslexic child (Laurent) was impressively impaired on metaphonological tasks, the child with a surface dyslexia pattern (Nicolas) demonstrated completely normal metaphonological performance. Similar results were reported by [Hanley and Gard \(1995\)](#) with undergraduate students. As the same tasks were used in both dyslexic participants, the absence of a phonological impairment associated with surface dyslexia may not easily be attributed to a lack of sensitivity of the tasks. The existence of contrasted reading profiles was thus confirmed by these studies. Additionally, [Valdois et al. \(2003\)](#) reported a double dissociation. Indeed, contrary to Laurent, Nicolas demonstrated an impairment on report tasks, in which he was asked to report as many letters as possible from a briefly visually displayed array of consonants. [Valdois et al.](#) interpreted this observation as reflecting a visuo-attentional deficit. This hypothesis will be discussed in further details in Chapter 2.

These single-case studies have highlighted the heterogeneity of the dyslexic population. The existence of opposite patterns of reading, such as phonological and surface dyslexia, is suggestive of the need for a multifactorial causal perspective ([Coltheart & Jackson, 1998](#)). However, pure cases of either phonological or surface dyslexia were relative infrequent in comparison to the mixed profile ([Castles & Coltheart, 1993](#); [Manis, Seidenberg, Doi, McBride-Chang, & Petersen, 1996](#); [Sprenger-Charolles et al., 2000](#); [Stanovich, Siegel, & Gottardo, 1997](#)), in which the reading of all types of items is affected². Moreover, the heterogeneity within each sub-type has also been acknowledged. Following [Coltheart and Jackson \(1998\)](#), we thus consider these sub-types as a convenient shorthand to quickly communicate major features of the reading pattern³.

²Note however that the proportion of pure cases largely depends on the method used to classify (classical vs. regression method; see [Genard et al., 1998](#); [Genard, 2000](#)) as well as the language and the comparison group (age- vs. reading-level matched controls) considered.

³This does not mean that there is no theoretical interest in identifying well-defined sub-types, possibly related to different aetiologies. On the contrary, sub-typing bears on the essential issue of whether or not developmental dyslexia is a unitary syndrome (e.g. [Bosse et al., 2007](#); [Snowling, 2001](#); [Vellutino et al., 2004](#); [Wolf & Bowers, 1999](#)). It has also been widely advocated that there is no direct relation between the nature of the behavioural dysfunction and the nature of the damaged underlying component ([Caramazza, 1986, 1992](#)). It follows that the interpretation of a patient's performance in terms of disruption to a particular cognitive component must be constrained by converging evidence from a variety of different tasks ([Caramazza &](#)

1.3 Theoretical accounts of dyslexia

Various theoretical hypotheses have been proposed to account for the reading retardation observed in dyslexia. We will first describe the most prominent theoretical conception of dyslexia: the phonological theory. As our dissertation is essentially dedicated to visual and attentional processing, we will further focus the discussion to theories specifically dealing with those aspects, and leaving out of our scope theoretical accounts that do not primarily address visual processing, such as the cerebellar theory (Nicolson, Fawcett, & Dean, 2001), as well as amodal versions of the magnocellular (Stein & Walsh, 1997; Stein, 2001) and attentional (Facoetti, Lorusso, Cattaneo, Galli, & Molteni, 2005; Hari, Renvall, & Tanskanen, 2001) hypotheses.

The phonological theory

The most widely accepted hypothesis with respect to the cognitive origin of developmental dyslexia is the phonological deficit hypothesis (Ramus, 2001a, 2003; Snowling, 1981; Stanovich, 1988; Stanovich & Siegel, 1994; Vellutino et al., 2004). The phonological theory originates in the fact that reading is an oral language activity. Phylogenetically as well as ontogenetically, the written code is secondary to the oral language, which is naturally learned since birth. Indeed, in all languages, the written code is a transcription of oral language units. In alphabetical systems, the basic graphic unit is the grapheme, which corresponds to a phoneme, the basic unit of the phonological system of a given language. It follows logically that any cause affecting the mapping between graphemes and phonemes would be strongly detrimental for the acquisition of fluent reading. Following the phonological hypothesis, dyslexics' reading and spelling problems are related to a deficit in phonological language skills.

Hence, large group studies have demonstrated that dyslexics differ from normal readers in those aspects of reading that place heavy demands on phonological processes. In a large review of the literature, Rack, Snowling, and Olson (1992) showed that a strong and reliable reading problem is observed on pseudo-words. This deficit remains significant when dyslexic participants are compared to younger reading level-matched controls participants. These results were confirmed by a meta-analysis of the same studies, including a total of 1,183 participants

Hillis, 1990). Consequently, the relevance of sub-typing is largely reduced when the different subtypes are only defined by comparing performances obtained when reading lists of irregular words vs. pseudo-words, as made in numerous studies. In those cases, I consider sub-types just as a shorthand.

(van Ijzendoorn & Bus, 1994). These authors further point out a significant impact of the nature of the test used to match the groups. The effect size of the deficit was larger in studies matching groups on complex word reading, instead of simple words or words in context (sentences).

Following the phonological theory, the difficulties encountered by the dyslexic children on pseudo-words stem from a specific and severe inability to use grapheme-to-phoneme conversion rules. The phonological theory further postulates that this impairment arises from deficiencies in phonemic analysis and verbal short-term memory. Phonemic analysis skills are required to allow the matching between graphemes and phonemes. Moreover, when this matching is done, the resulting phonemes must be assembled, an operation that relies on verbal short-term memory. Accordingly, numerous studies have shown that, compared to normal readers, developmental dyslexic children are impaired in tasks requiring the manipulation of phonemes, such as non-word repetition (Elbro, Borstom, & Petersen, 1998; Snowling, 1981), phonemic fluency (Frith, Landerl, & Frith, 1995), picture naming (Snowling, Watgendonk, & Stafford, 1988), phonemic awareness and verbal short-term memory (e.g. Griffiths & Snowling, 2002). Furthermore, studies on normal reading acquisition suggest a causal relationship between phonological processing skills and reading abilities: phonological awareness is strongly related to reading progress (e.g. Morais, Alegria, & Content, 1987a, 1987b; for a review, see Goswami & Bryant, 1990; see also Morais, Cary, & Bertelson, 1979), children's knowledge of the phonological structure of their language is a good predictor of early reading ability (Bradley & Bryant, 1983; Elbro et al., 1998) and phonemic awareness training improves learning to read (Bradley & Bryant, 1983; for a meta-analysis, see Ehri et al., 2001; see also Castles & Coltheart, 2004).

The phonological theory relies also on the observation that phonological deficits were consistently observed in studies in which different theoretical accounts were simultaneously assessed (Ramus, Pidgeon, & Frith, 2003; Ramus, Rosen, et al., 2003; White et al., 2006). In those studies, three leading theories of developmental dyslexia were assessed: (i) the phonological theory⁴, (ii) the magnocellular theory (see Section 1.3) and (iii) the cerebellar theory⁵. Note however that the visual atten-

⁴In those three studies, 'phonological' tasks included phonological awareness and short-term memory tasks, but also rapid automatic naming (RAN). This is controversial in regard of the proposal, made by Wolf and Bowers (1999), that a RAN impairment might be a second core deficit of dyslexia (see below). Ramus (2003) and White et al. (2006) also considered pseudo-word reading as a phonological task.

⁵Following the cerebellar theory, disorders of the cerebellar development can in fact cause the impairments in reading and writing characteristic of dyslexia. This

tion hypothesis (also described in Section 1.3) was not tested. [Ramus, Rosen, et al. \(2003\)](#) reported significant phonological deficits in all of the 16 university students with dyslexia they tested. In contrast, sensory and motor disorders were observed in only some individuals. Results obtained on children were however less clear-cut. A phonological deficit was observed in the majority (77%) of the children who took part in the study by [Ramus, Pidgeon, and Frith \(2003\)](#), in which the phonological theory and the cerebellar theory were contrasted. However, the criterion for a deficit was rather liberal: scores deviating more than 1 standard deviation (SD) from the control means were considered as impaired. With the same criterion, 13 dyslexics out of 22 (59%) demonstrated motor impairments. [White et al. \(2006\)](#) reported also a significant phonological impairment in 52% of their 23 dyslexic participants, with the more stringent criterion of a 1.65 SD deviation. Similarly to the adult study, sensory and motor disorders were observed in only a few individuals. In both studies, phonological scores were the best predictor of reading achievement, explaining the major part of the variance ([Ramus, Rosen, et al., 2003](#); [White et al., 2006](#)).

In further support to this view are also neurofunctional data showing that impaired reading of alphabetic scripts is associated with dysfunction of left temporo-parietal brain regions (e.g. [Shaywitz et al., 1998](#); for recent reviews, see [Démonet et al., 2004](#); [Shaywitz & Shaywitz, 2005](#)), highlighted in Figure 1.2. These regions perform phonemic analysis and conversion of written symbols to phonological units of speech (grapheme-to-phoneme conversion); the two central cognitive processes assumed by the phonological theory to form the core deficit of dyslexia. [Paulesu et al. \(2001\)](#) further suggest that the hypo-activation observed in left perisylvian regions may serve as a universal biological marker of dyslexia. This universal view has nevertheless been challenged by the observation of a different pattern of brain activations in chinese dyslexics, including

hypothesis initially stems from the observation of difficulties showed by dyslexic children in information processing speed, memory, motor skill and balance ([Nicolson et al., 2001](#)). This has led [Nicolson and Fawcett \(1990\)](#) to propose that dyslexic children have difficulties in automatising skills, whether or not the skill is in the literacy domain, an ability thought to depend upon the cerebellum. In order to explain the reading deficits, the initial version of the cerebellar theory hypothesised that motor problems (consecutive to the cerebellar dysfunction) affecting speech articulation would be detrimental for the development of phonological skills, which in turn would impair reading acquisition. This hypothesis relies on the assumption that the acquisition of internal representations of speech (i.e., phonology) depends on explicit speech articulation, which remains controversial (see e.g. [Ramus, Pidgeon, & Frith, 2003](#)). In a more recent version, the emphasis has been put on the key role of language-related regions of the cerebellum ([Nicolson & Fawcett, 2006](#)).

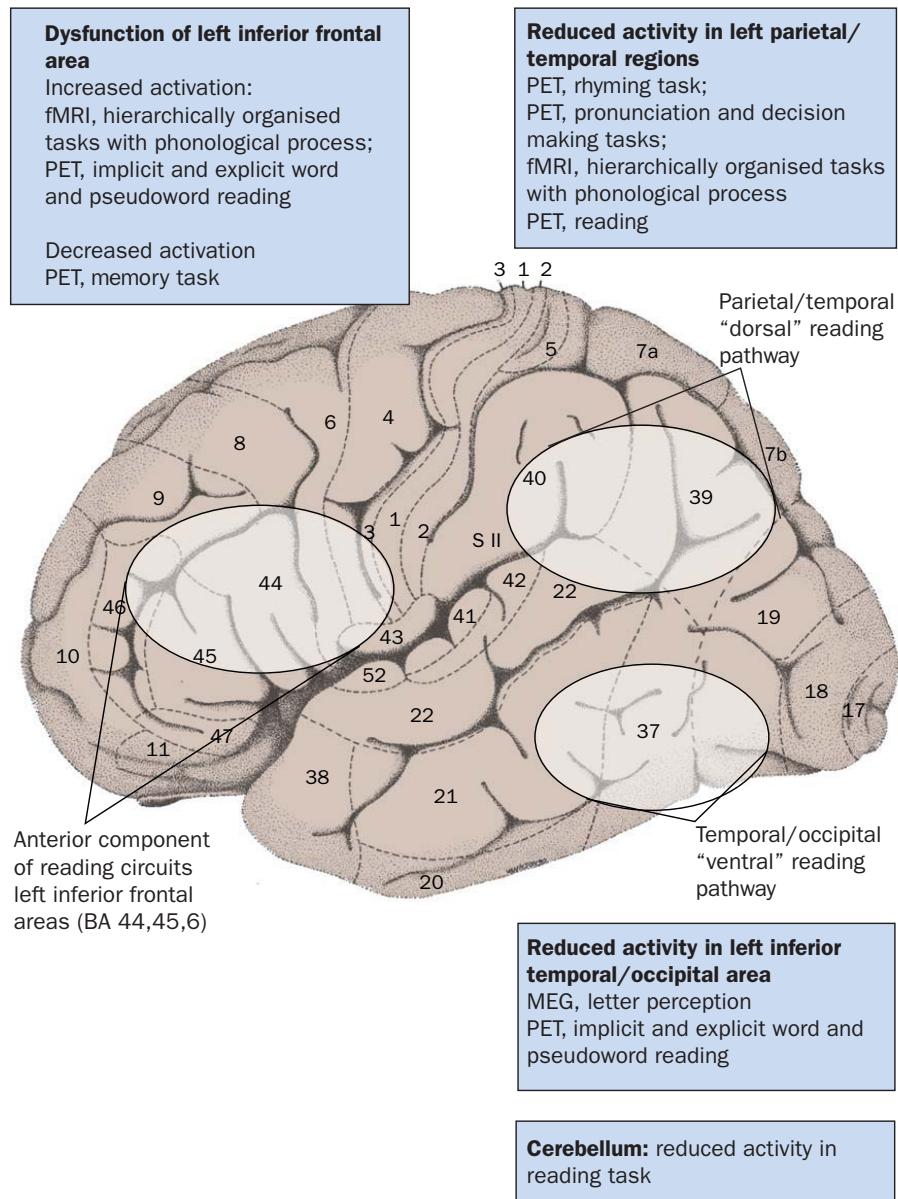


Figure 1.2: Summary of the areas of the left cerebral hemisphere showing abnormal activation in adults with dyslexia compared with controls. Digits represent the Brodmann classification of cerebral areas. Boxes explicit the nature of the abnormal activation (hyper vs. hypo-activation), the technique used (PET-scan vs. fMRI) as well as the experimental tasks. Reprint from [Démonet et al. \(2004\)](#).

an hypo-activation in the left middle frontal gyrus (Siok, Perfetti, Jin, & Tan, 2004; for further discussion of these results, see the comment of Ziegler, 2005 and the answer of Perfetti, Tan, & Siok, 2006). Other abnormal activations (depicted in Figure 1.2) were observed in the left inferior frontal area, as well as in the left inferior temporal/occipital area. The former is implicated in the output of phonological and articulatory aspects. The hyper-activation observed in this region has been interpreted as reflecting compensation mechanisms (Brunswick, McCrory, Price, Frith, & Frith, 1999; Shaywitz et al., 1998). The latter has been related to the automatic access to the visual word form, the representation of letter strings as an ordered set of abstract letter identities (Cohen et al., 2000, 2002, 2003; Dehaene, Le Clec'H, Poline, Le Bihan, & Cohen, 2002; McCandliss, Cohen, & Dehaene, 2003, but see e.g. Price & Devlin, 2003).

Finally, Wolf and Bowers (1999) have proposed an additional core deficit of dyslexia, independent of phonology. They interpreted the robust impairment observed in dyslexics on naming times in *rapid automatised naming* tasks (RAN: Denckla & Rudel, 1976) of frequent items (letters, colours or objects) as indicating a second, independent, deficit. However, this hypothesis has been challenged on theoretical, interpretative, and methodological grounds (see e.g. Vellutino et al., 2004). The major problem it faces is that RAN tasks are multi-determined. The cognitive components that drive the relation between RAN and reading has currently not been established (see Powell, Stainthorp, Stuart, Garwood, & Quinlan, 2007; Savage, Pillay, & Melidona, 2007, for recent attempts of experimental clarification). As a consequence, RAN performance has sometimes been integrated within the phonological framework as reflecting an additional problem of —poor and/or slow— access to the phonological representations (Wagner & Torgesen, 1987). Other interpretations include (poorly specified) cognitive deficits interfering with the quality of orthographic representations themselves and with the formation of links between orthographic and phonological representations (Wolf & Bowers, 1999) or a more general processing speed impairment (e.g. Catts, Gillispiie, Leonard, Kail, & Miller, 2002).

In summary, there is a large amount of evidence demonstrating the robustness of phonological deficits in dyslexia. Also, the phonological skills explain a large and significant part of the reading performance. Finally, neurofunctional markers have been provided. As a consequence, it is classically admitted that reading difficulties in most children are caused by deficits in phonological coding. An even stronger version of the hypothesis states that the phonological deficit is the *sole* core deficit of dyslexia (see e.g. Griffiths & Snowling, 2002; Shaywitz & Shaywitz,

2005; for a critical discussion, see e.g. [Ramus, Rosen, et al., 2003](#); [Valdois et al., 2004](#)). However, other theories have been proposed to account for the diversity of impairments described in other domains than oral language. These challengers of the phonological theory do not dispute the existence of a phonological deficit and its contribution to reading retardation (but see e.g. the visual attention span hypothesis, described in Chapter 2). Rather, most of these tried to also explain the plethora of other problems that children with dyslexia suffer.

Visual impairments and the magnocellular theory

At the origin of the magnocellular hypothesis is the observation of fine-grained visual impairments in individuals with dyslexia. Indeed, there is now converging evidence that some individuals with dyslexia suffer from subtle impairments in visual processing, independently of any sensorial or peripheral defect. This set of data has been formalised by [Stein and Walsh \(1997\)](#) into the magnocellular theory of dyslexia (see also [Livingstone et al., 1991](#); [Stein, 2001, 2003](#)).

The visual system

The primate visual system, schematically depicted in Figure 1.3, is mainly composed of two major processing pathways that remain largely segregated and independent throughout the visual system. Within the retina, signals from photoreceptors pass through bipolar cells to ganglion cells, their axons forming the optic nerve, which projects principally to the lateral geniculate nucleus of the thalamus (LGN). The axons of LGN neurons project almost exclusively to the primary visual area, V1, where they terminate primarily in layer 4. The subdivision in two pathways begins in the retina but is most apparent, and was first discovered, in the LGN. The LGN anatomy is depicted in more detail in Figure 1.4. The LGN is composed of six different layers, with distinct anatomical as well as functional properties. Anatomically, cells in the ventral, or magnocellular (M), layers are larger than cells in the dorsal, or parvocellular (P), layers. In the retina and the LGN, the magno and parvo subdivisions differ physiologically in four major ways: colour selectivity, contrast sensitivity, temporal resolution, and acuity. This segregation, started in the retina, continues at least in V1, where magnocells project mainly to layer $4C\alpha$, and parvocells to layer $4C\beta$. The spatial contrast sensitivity curves of magno and parvocells of the LGN are shown in Figure 1.4. Detection of low spatial frequencies —at high temporal frequencies, not illustrated in the graph— is mediated by magnocells, while parvocells carried out

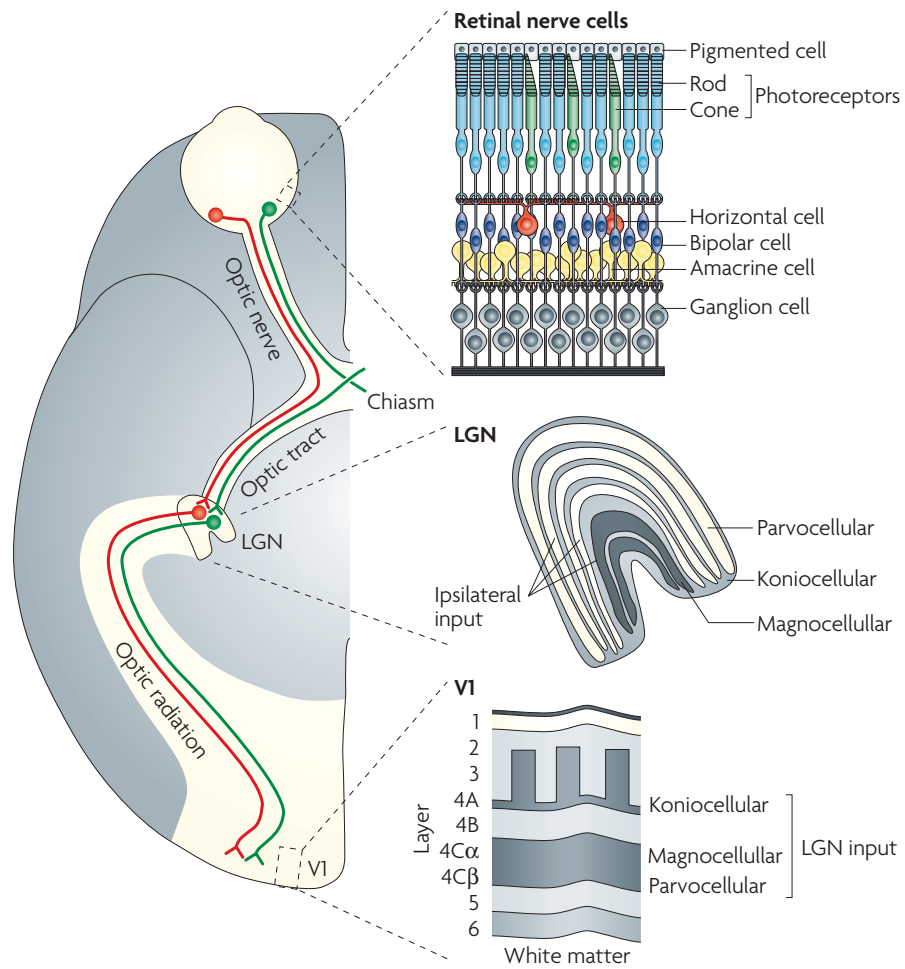


Figure 1.3: Basic architecture of the sub-cortical visual pathways. Reprint from Solomon and Lennie (2007).

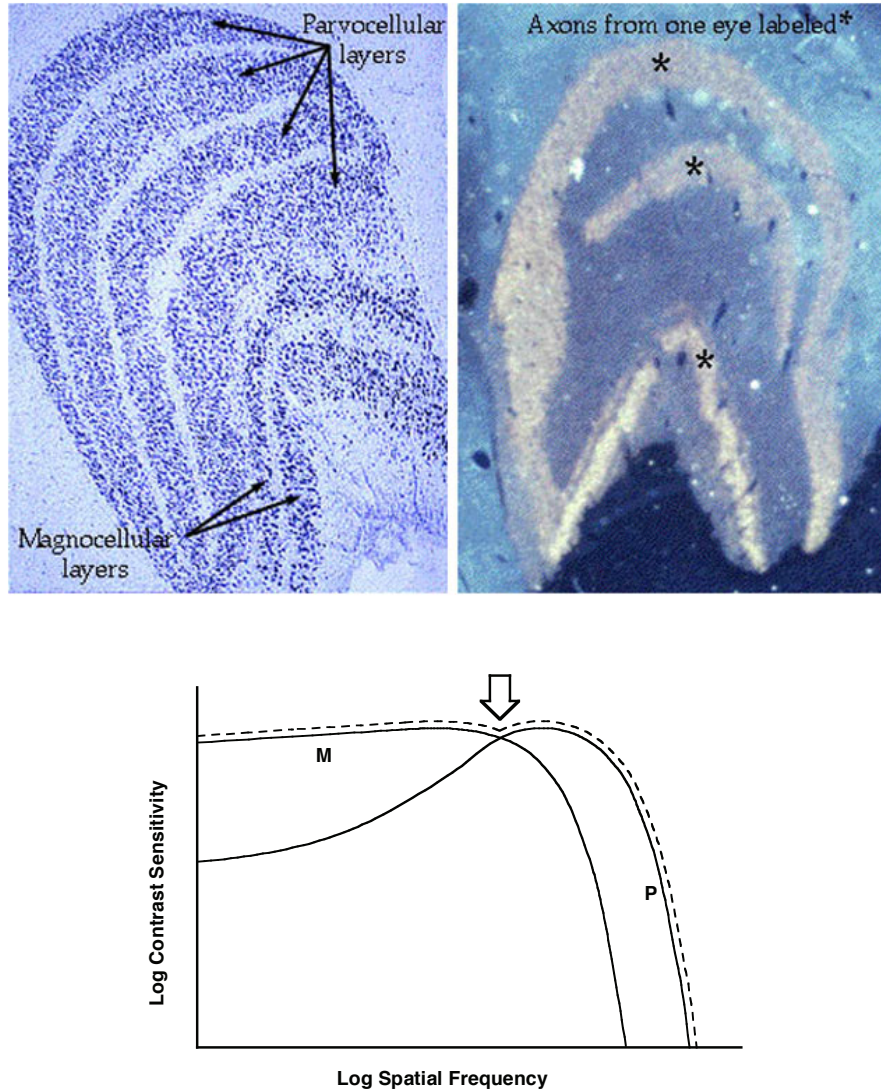


Figure 1.4: *Lateral Geniculate Nucleus of the thalamus. Histological slices (from <http://webvision.med.utah.edu/>) show separate magno- and parvocellular layers of the monkey LGN. Below is a graphical presentation (re-drawn from Skottun, 2000a) of the theoretical spatial contrast sensitivity curves of magno- (M) and parvo-cells (P) (solid lines) and their ‘envelope’ (dashed line). The transition point between the two systems is marked with an arrow. At frequencies below this point detection is mediated by the magnocellular system and at frequencies higher than this point detection is carried out by the parvocellular system.*

the detection of higher spatial frequencies —especially at low temporal frequencies— (Skottun, 2000a). This allows the possibility to investigate the integrity of both pathways with psychophysical procedures.

Starting from V1, there is a mingling of the M and P streams. However, additional processing streams have been identified in the visual cortex (see Figure 1.5). The dorsal stream, which connects V1 to the posterior parietal cortex (PPC), has been implicated in object localisation, motion perception, and goal-directed movements, as well as selective visual attention and the control of eye movements. The ventral stream, which connects V1 to the infero-temporal region, has been implicated in object recognition and colour processing. The predominant anatomical projection from V1 to the dorsal stream arises from the sub-cortical M stream.

Visual impairments and dyslexia

The interest for the magnocellular system in dyslexia really started with a study by Livingstone et al.. In 1991, they recorded visual evoked potentials when viewing counterphase flickering checkerboards at various luminance contrasts and temporal frequencies. Significant differences between dyslexic and control participants were observed at low contrast and high temporal frequencies. Livingstone et al. interpreted these result in support for a magnocellular impairment in dyslexia. They further reported anatomical evidence for a significant reduction of the size of the magnocells of the LGN in a post-mortem dissection of the brain of 5 dyslexic patients.

Following this study, the integrity of the magnocellular pathways as well as the visual dorsal stream has been extensively investigated in dyslexic people. The mainly used paradigms were luminance contrast sensitivity and coherent motion detection. Visual attention has also received recent interest, but will be discussed later. Contrasts thresholds were generally assessed with sinusoidal gratings of various spatial and temporal frequencies (see Figure 1.6 A and B). Cornelissen, Richardson, Mason, Fowler, and Stein (1995) first proposed to use random dots kinematograms (RDK) to investigate coherent motion perception. A RDK consists of an array of independently moving dots in randomly selected directions. For a given amount of dots, a coherent motion is introduced (see Figure 1.6 C). Coherent motion sensitivity is estimated as the percent of dots moving coherently in order to perceive the direction of the coherent motion. First described by Lovegrove, Bowling, Badcock, and Blackwood (1980), impaired contrast sensitivity was often reported in dyslexic individuals (e.g. Borsting et al., 1996; Edwards et al., 2004;

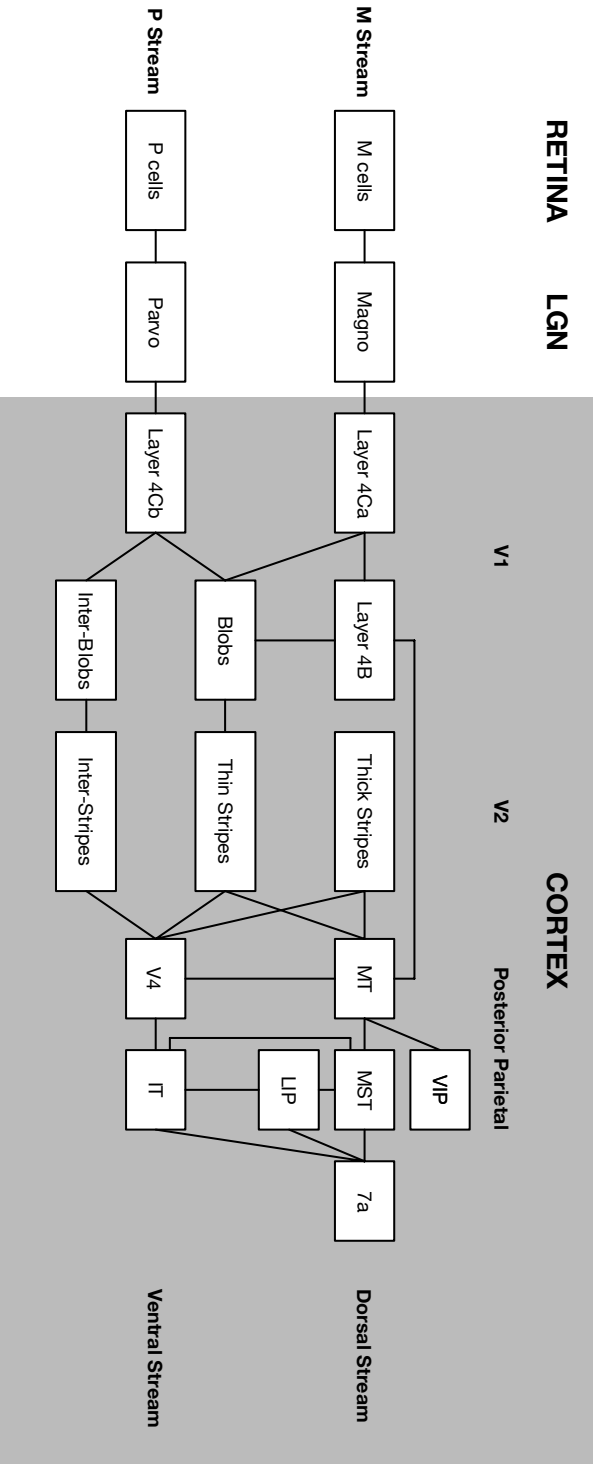


Figure 1.5: Schematic architecture of the ventral and dorsal pathways in the monkey visual system. LGN: lateral geniculate nucleus of the thalamus; V1: cortical visual area 1; V2: cortical visual area 2; V4: cortical visual area 4; M: magnocellular; P: parvocellular; MT: medial temporal area; VIP: ventral intraparietal lobe; MST: medial superior temporal area; LIP: lateral intraparietal cortex; IT: inferior temporal cortex; 7a: area 7a of the parietal cortex. Modified from [Boden and Giaschi \(2007\)](#).

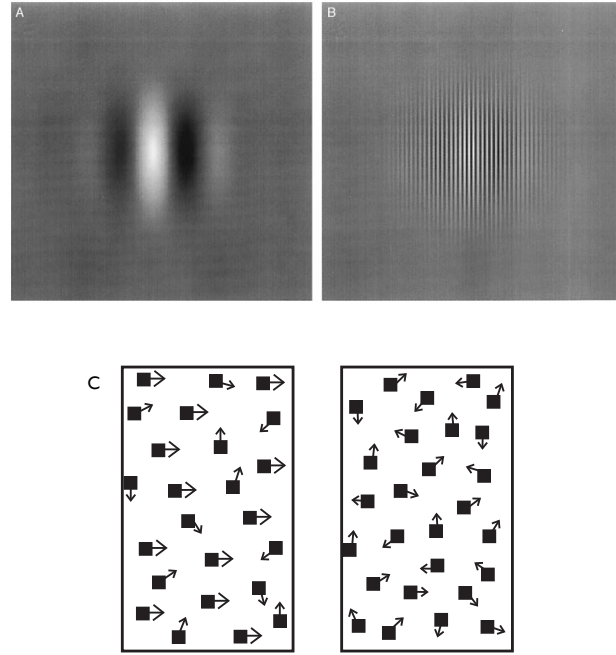


Figure 1.6: Examples of tasks used to assess the magnocellular system. (A and B) Gabor patterns used for contrast sensitivity estimation, reprint from [Ramus, Rosen, et al. \(2003\)](#): (A) low spatial frequency stimulus, targeting the magnocellular pathway; (B) high spatial frequency stimulus, targeting the parvocellular pathway. (C) Experimental display to assess coherent motion, reprint from [Hansen et al. \(2001\)](#). Arrows represent the vector motion of each dot during a given frame. The left panel depicts 50% coherent motion where half the dots (large arrows) are moving together in horizontal motion. Noise dots move in random directions. The non-target random dot kinematogram patch, showed in the right panel, has an average coherence value close to 0%. Classical tasks are spatial or temporal two-alternatives forced choice tasks, coupled with a thresholding estimation procedure.

Livingstone et al., 1991; Slaghuys & Ryan, 1999). A robust deficit was also observed on visual motion perception (e.g. Cornelissen & Hansen, 1998; Cornelissen, Hansen, Hutton, Evangelinou, & Stein, 1998; Cornelissen et al., 1995; Talcott, Hansen, Assoku, & Stein, 2000; Wilmer, Richardson, Chen, & Stein, 2004). Since then, a large number of behavioural and neurofunctional empirical evidence have been interpreted in support of a magnocellular disorder in dyslexia (reviewed in Stein, 2001; Stein & Walsh, 1997). It has for example been shown that coherent motion thresholds are predictive of the reading performance (e.g. Boets, Wouters, Wieringen, & Ghesquière, 2006; Talcott, Witton, et al., 2000; Witton et al., 1998 but see e.g. Hutzler, Kronbichler, Jacobs, & Wimmer, 2006 for challenging evidence).

Despite the empirical evidence of a magnocellular/dorsal stream impairment, how the visual magnocellular system could be involved in reading is still not immediately obvious. Stein and Walsh (1997) proposed that the answer lies in the projections from the magnocellular layers of the LGN to the PPC (see also Stein, 2001, 2003). As the PPC is known to be important for normal eye-movement control, visuospatial attention and peripheral vision, they suggested that a magnocellular disorder may impact reading through these PPC functions. Indeed, poor binocular control (e.g. Stein, Richardson, & Fowler, 2000), eye movements abnormalities (Biscaldi, Fischer, & Hartnegg, 2000; Biscaldi, Gezeck, & Stuhr, 1998; Fischer & Hartnegg, 2000; Pavlidis, 1981) as well as particular attention deficiencies (see Section 1.3) has been described in dyslexic persons. Similarly, Boden and Giaschi (2007) recently reviewed and investigate several different possible roles of the visual M-pathway in reading. Most rely on a close connection between the M-pathway and the dorsal visual stream. Boden & Giaschi suggest that one of the most promising lines of research to investigate the contribution of the M-stream to reading is closely tied to visual attention. Finally, in an amodal version of the theory, Stein and Walsh (1997) further proposed that the deficit may affect more generally (visual and auditory) magnocellular systems, leading to a *general timing deficit* hypothesis. It remains to be shown empirically, however, that the M-stream is involved in normal reading and that M-stream visual deficits contribute to reading acquisition problems.

Moreover, the notion of a magnocellular impairment has also been challenged on various grounds. First of all, a number of studies have failed to find evidence of a M-stream deficit in developmental dyslexia (e.g. Amitay, Ben-Yehudah, Banai, & Ahissar, 2002; Bednarek & Grabowska, 2002; Ben-Yehudah, Sackett, Malchi-Ginzberg, & Ahissar, 2001; Farrag, Khedr, & Abel-Naser, 2002; Hawelka & Wimmer, 2005; Ra-

mus, Rosen, et al., 2003; Williams, Stuart, Castles, & McAnally, 2003; White et al., 2006). Different methodological concerns have been risen (Roach, Edwards, & Hogben, 2004; Stuart, McAnally, & Castles, 2001). Ben-Yehudah et al. (2001) have shown that the observation of a magnocellular-like deficit is observed only on temporal, but not spatial, two-alternatives forced choice tasks (see also Ben-Yehudah & Ahissar, 2004; Ram-Tsur, Faust, & Zivotofsky, 2006), suggesting that the deficit may in fact be related to cognitive functions required to retain and compare elements. A. Sperling, Lu, Manis, and Seidenberg (2005, 2006) argued that apparent M-stream impairments are due to deficits in perceptual noise exclusion. In a extensive review of contrast sensitivity —the most direct test of the magnocellular function— in dyslexia, Skottun (2000a) concludes that the evidence from contrast sensitivity studies for a magnocellular deficit associated with dyslexia is highly conflicting. Most studies either showed no deficit at all, or a deficit inconsistent with the predictions of the magnocellular hypothesis (see Stein, Talcott, & Walsh, 2000; Skottun, 2000b for further replies). Finally, the identity made between the sub-cortical M-stream and the cortical dorsal stream may also be problematic. Indeed, “the dorsal stream, in addition to magnocellular input, receives inputs which can be traced back to the parvocellular and koniocellular systems of the LGN, and the ventral stream (...) receives about equally strong inputs of magno- and parvocellular origin” (Skottun & Skoyles, 2006b, p. 173). Therefore, joining the magnocellular system with the dorsal stream into a generalised “magnocellular pathway” is problematic. It is thus not obvious to interpret defect in functions supported by the dorsal stream (such as motion perception) as automatically reflecting a basic magnocellular impairment.

In summary, there is a large amount of evidence demonstrating visual impairments in dyslexic participants. The magnocellular theory offers a very appealing framework to integrate various impairments in a unique explicative scheme. However, the precise nature of these visual defects is not well understood. Further research is required to clarify both the diversity of the visual impairment observed in dyslexics and their impact on reading acquisition. More specifically, the question is open of whether or not these deficits reflect an impairment of the magnocellular system.

Attentional impairments and the visual attention deficit hypothesis

Visual attentional functions have only been sporadically investigated in dyslexia until recently. The proposal, made by Stein and Walsh (1997; see also Hari & Renvall, 2001; Vidyasagar, 1999), that visual attention

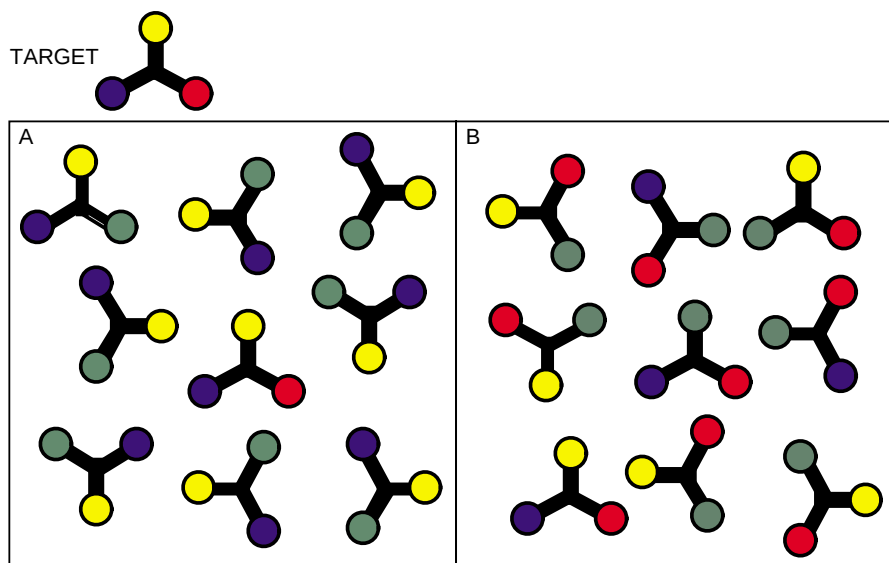


Figure 1.7: *Examples of visual search tasks. The target is shown in the upper left corner. In (A), the search is easy because the target is defined by a unique red element. In (B), the search is much less efficient because the target is not defined by a unique distinctive feature, but by a conjunction of features. Modified from Wolfe (2003).*

may potentially mediate the relation between a subcortical magnocellular impairment and reading acquisition has certainly participated to the recent interest for visual attention in dyslexia. The literature on visual attention in dyslexia is very mixed in both the methodology and outcome. Two broad classes of paradigms were mainly used to investigate visual attention in dyslexic people: visual search tasks and cue-target paradigms.

In a typical experiment on visual search, the subject must indicate ‘as quickly as possible’ whether a target is present in a display. Treisman and Gelade (1980) introduced a widespread distinction between feature and conjunction search. Both are illustrated in Figure 1.7. “In *feature* search, the target differs from the distractors by possessing a simple ‘physical’ feature (e.g. a particular colour, size or curvature) not shared by any of the distractors. In such conditions, the target phenomenally may appear to pop out from the background of distractors without any need to scan the display by saccadic eye movements or shifts of attention. Behaviourally, search can be fast and little affected by display size. In *conjunction* search, the target differs from the distractors by showing

a predefined conjunction of physical features (e.g. both a particular colour and a particular shape), but the target is not unique in any of the component features of the conjunction (i.e. in colour or in shape). In such conditions, the search process may be effortful and appear to consist in scrutinising the display part by part or even item by item. Behaviourally, search times tend to be longer, and positive and negative mean reaction times tend to be approximately linear functions of display size with substantial slopes.” (Bundesen & Habekost, 2005, pp. 107–108). It has often been suggested that two different mechanisms, one parallel and pre-attentive and the other serial and implicating attention, underlie these contrasting patterns (Treisman & Gelade, 1980)⁶. Visual search abnormalities have been consistently described in individuals with dyslexia in tasks involving search for a conjunction of features (Buchholz & McKone, 2004; Marendaz, Valdois, & Walch, 1996; Sireteanu, Goebel, Goertz, & Wandert, 2006; Vidyasagar & Pammer, 1999), pointing to an impairment in visual attention. Moreover, Iles, Walsh, and Richardson (2000) showed that visual search difficulties were restricted to a subgroup of dyslexics also impaired on motion perception.

Different aspects of attention were further investigated with cue-targets paradigms. In such paradigms, the target is preceded by a cue that gives some indications on the locus of appearance of the target. The target is classically a light dot, and the task requires to react as quickly as possible when the dot appears. Different aspects of attention were studied by varying the characteristics of the cue: type (central, peripheral, ...), validity, duration of appearance, inter stimulus interval (ISI) and stimulus onset asynchrony (SOA), ...

Covert orienting deficits were repeatedly described in poor readers and individuals with dyslexia (Buchholz & Aimola Davies, 2005, 2006; Facoetti, Paganoni, Turatto, Marzola, & Mascetti, 2000; Facoetti, Turatto, Lorusso, & Mascetti, 2001; Facoetti et al., 2003). For example, Facoetti, Paganoni, Turatto, et al. (2000) presented ten dyslexic children and ten age-matched normal readers with a simple detection task. The target was a light dot appearing in one of two circles displayed eccentrically, one in each visual hemifield. The location of appearance was cued with 80 % validity by an arrow appearing either above one of the circles (peripheral cue) or at fixation (central cue), and the SOA varied between 136 and 1000 ms. Finally, in a neutral condition, both circles were simultaneously cued. The control participants demonstrated the classical

⁶ However, the strict dichotomy between two distinct mechanisms has been challenged (e.g. the meta-analysis by Wolfe, 1998; for reviews, see e.g. Bundesen & Habekost, 2005; Wolfe, 2003; see also Bundesen, 1990, 1998; Duncan & Humphreys, 1989 for a formal demonstration).

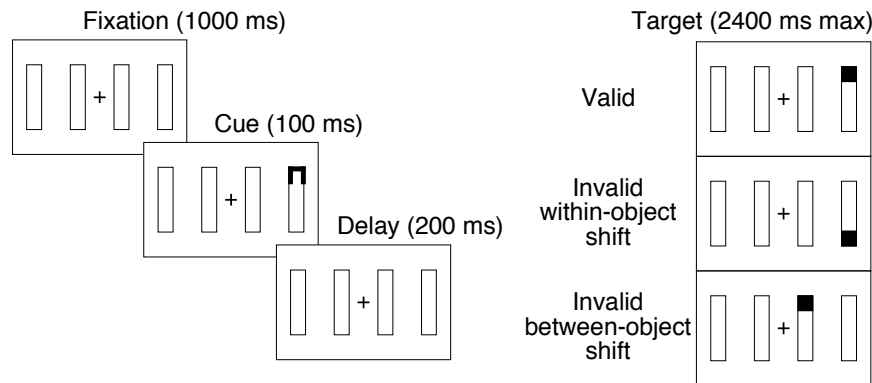


Figure 1.8: Schematic illustration of the precueing paradigm used by [Buchholz and Aimola Davies \(2005, 2006\)](#) to investigate space-based and object-based attention. The three trial conditions (valid, within-object shift, and between-object shift trials) are illustrated on the right. See text for details. Redrawn from [Buchholz and Aimola Davies \(2006\)](#).

effect: reaction times were shorter for valid cues in comparison to neutral cues, and were longer for invalid cues trials. Dyslexics' reaction times were globally longer. Moreover, dyslexic participants did not exhibit any effect of the validity of the cue for peripheral cues at the shortest SOAs (136 and 238 ms), reflecting a deficit in automatic orienting. With the same paradigm, [Facoetti et al. \(2001\)](#) showed hemifields differences: Dyslexic children showed a peripheral cue-effect in the left but not the right visual hemifield. The authors speculated that this lateral imbalance may possibly stem from a right posterior parietal deficit, leading to a decreased inhibitory influence on the contralateral hemisphere.

The preceding attentional difficulties in dyslexia are all related to a space-based component of attention, that is, to attention selecting a particular spatial region in the visual field from which information will be processed. However, visual attention can also be deployed to visual features such as colour or motion (feature-based attention), or in an object-based fashion, in which whole objects, or perceptual groups, that have been organised preattentively, are selected (for reviews, see e.g. [Hopf et al., 2006](#); [Yantis & Serences, 2003](#)). Difficulties with both space- and object-based covert shifts of attention have been demonstrated in adult dyslexics who were selected to have phonological difficulties ([Buchholz & Aimola Davies, 2005, 2006](#)). To investigate simultaneously space-based and object-based attention, [Buchholz and Aimola Davies](#) used a precueing paradigm developed by [Egley, Driver, and Rafal \(1994\)](#). In each trial,

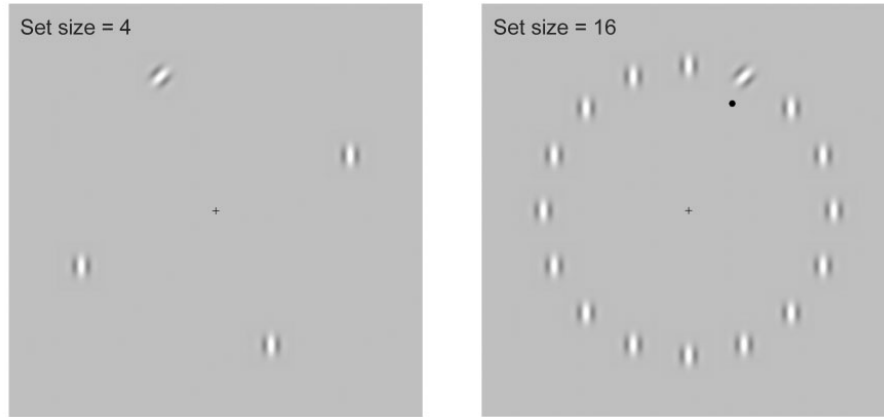


Figure 1.9: Examples of search arrays used by [Roach and Hogben \(2004, 2007\)](#). The left panel illustrates a uncued search array for set size 4. The right panel shows a cued search array for set size 16. In each case, all distractors are vertically oriented while the target is tilted 45° clockwise. While in the experiment cue and visual search array appeared successively, the two frames are shown superimposed upon one another in the right-hand panel to illustrate the spatial relationship between the cue and the target. Reprint from [Roach and Hogben \(2007\)](#).

four boxes were displayed, two in each visual hemifield (see Fig. 1.8). One end of a given box was further cued by increasing the thickness of the border. Depending on the condition, the target appeared at the cued location (valid trial) or at an uncued condition (invalid trial). Finally, two types of attentional shift are distinguished: in the invalid condition, the target appeared equally often either at the opposite end of the cued object (within-object shift of attention) or in the adjacent object within the same hemifield (between-object shift of attention). Both types of shifts of attention were of equal distance. Space-based and object-based shifts of attention were respectively investigated by comparing shifts in direction to the center vs. the periphery of the visual fields, and within- vs. between-object shifts. Dyslexic participants showed slower responses to between-object shifts of attention in the left visual field and difficulty engaging stimuli in the periphery, but not the fovea.

Other studies suggested a slow and difficult focusing of attention, and impaired filtering of irrelevant elements ([Facoetti, Paganoni, Turatto, et al., 2000](#); [Facoetti et al., 2003](#)). By combining a visual search task with a cueing paradigm, [Roach and Hogben \(2004, 2007\)](#) demonstrated a marked spatial-cueing deficit. They used a visual search task of a tilted Gabor patch amongst a various number of vertical Gabor patches (see

Figure 1.9). The threshold tilt required to reliably discriminate the direction of tilt of the target irrespective of its location was estimated for each set size (1 to 16 elements). Finally, in half the trials, a 100% valid cue was added. The cue effect was thus observed as a decrease in threshold tilt for cued trials. Whereas uncued search results were equivalent for dyslexic and normal adult readers, the majority of dyslexic individuals failed to display a comparable benefit when the location of the target was indicated by the appearance of the brief peripheral cue. Using signal detection theory to model the participants' search performance, Roach and Hogben (2007) convincingly demonstrated that the cueing deficit observed in dyslexic individuals reflects their inability to filter out the distractor stimuli.

A series of studies by Facoetti and his colleagues also suggest that individuals with dyslexia distribute their attention differently than normally reading controls, either in a more distributed and sluggish fashion (Facoetti, Paganoni, & Lorusso, 2000; Facoetti et al., 2003, 2005) or asymmetrically to the right visual field (Facoetti & Molteni, 2001; Facoetti, Paganoni, & Lorusso, 2000; Lorusso et al., 2004). Signs of left 'mini-neglect' were also reported in dyslexic patients by Hari et al. (2001). These authors defined the left-sided 'mini-neglect' as "a right-sided spatial bias in selecting and processing visual information" (Hari et al., 2001, p. 1377) on the basis of qualitative similarities between neglect patients and dyslexic individuals. They tested dyslexic adults with two tasks known to be affected in neglect patients. In the *temporal order judgement task*, two bars are presented, one in each visual field. Subjects are required to indicate which of the two appeared first. The SOA between the stimuli is then systematically varied. At short SOAs, dyslexic participants tended to report more right than left stimuli precedence. They obtained similar results in a *line motion illusion task*. Left mini-neglect was further observed in line bisection (Sireteanu, Goertz, Bachert, & Wandert, 2005; Sireteanu et al., 2006). Hari et al. (2001; see also Hari & Renvall, 2001) interpreted this left mini-neglect as reflecting a visual attentional problem, possibly stemming from a mild right parietal lobe dysfunction. In line with these results, some dyslexic children were shown to exhibit left inattention in flanker and cue-target reaction time tasks, associated with over-distractibility in the right visual field (Bednarek et al., 2004; Facoetti & Turatto, 2000; see also the literature reviewed above). Also in agreement are the reports of prolonged attentional blink⁷ in dyslexic children (Buchholz & Aimola Davies, 2007;

⁷An 'attentional blink' can be measured with a dual task procedure consisting of two targets, the first one to be identified and the second to be detected (Duncan,

Hari, Valta, & Uutela, 1999; Visser, Boden, & Giaschi, 2004; but see Lacroix et al., 2005). However, other studies did not find any sign of attentional imbalance between hemifields (Judge, Caravolas, & Knox, 2007; Rutkowski, Crewther, & Crewther, 2003; Sireteanu et al., 2006).

To account for these results, Hari and Renvall (2001) have suggested that dyslexic individuals may suffer from a *sluggish attentional shifting* mechanism, the SAS theory of dyslexia. This attentional deficit, potentially supported by a mild right parietal lobe dysfunction, is putatively due to poor magnocellular input to the dorsal visual stream (for a review, see Jaśkowski & Rusiak, 2005). Due to this, the attention of dyslexic subjects, once engaged, cannot easily disengage, and vice versa. Following Hari & Renvall, this sluggish shifting would “prolong sensory input chunks, thereby degrading cortical representations essential for fluent reading. (...) Within the SAS framework the same core deficit in the M-system could have independent effects at various processing levels, and all these effects — direct sensory impairments, attention-related rapid stimulus sequence processing deficits, and prolonged input chunks — could contribute to the reading impairment, thereby forming a cascade of causal factors.” (p. 530). This deficit may be apparent in all modalities. Accordingly, similar attentional impairments were observed in visual and auditory modalities (Facoetti et al., 2003, 2005). For Hari and Renvall (2001), one of the main consequences of prolonged input chunks would be distorted phonological representations, leading to poor phonological awareness. Following this account, visual attention, the magnocellular and phonological theories are thus linked.

A slightly different theoretical account was proposed by Vidyasagar (1999, 2001, 2004, 2005). Similarly to Hari & Renvall, Vidyasagar’s proposal originates in the distinction between magno- and parvocellular pathways, and their respective predominant projections to the dorsal and ventral visual streams. However, they differ in the way the role of attention in reading is conceived. Vidyasagar (1999, p. 68) proposed “that the visual system may exploit this dichotomy of a fast magnocellular/transient channel and a slower parvocellular/sustained channel for the purposes of selective attention. The faster transmission and the spatial coding properties of the dorsal stream are ideal to provide a feedback to one of the earlier stages in the pathway (say, the striate cortex) to selectively facilitate regions of interest before further processing in the ventral stream. This means that, with the initial barrage of visual in-

Ward, & Shapiro, 1994). For 400-600 ms after the first target, the subject is transiently ‘blind’ to other targets. This ‘attentional dwell time’ is caused by capacity limitations (Marois & Ivanoff, 2005).

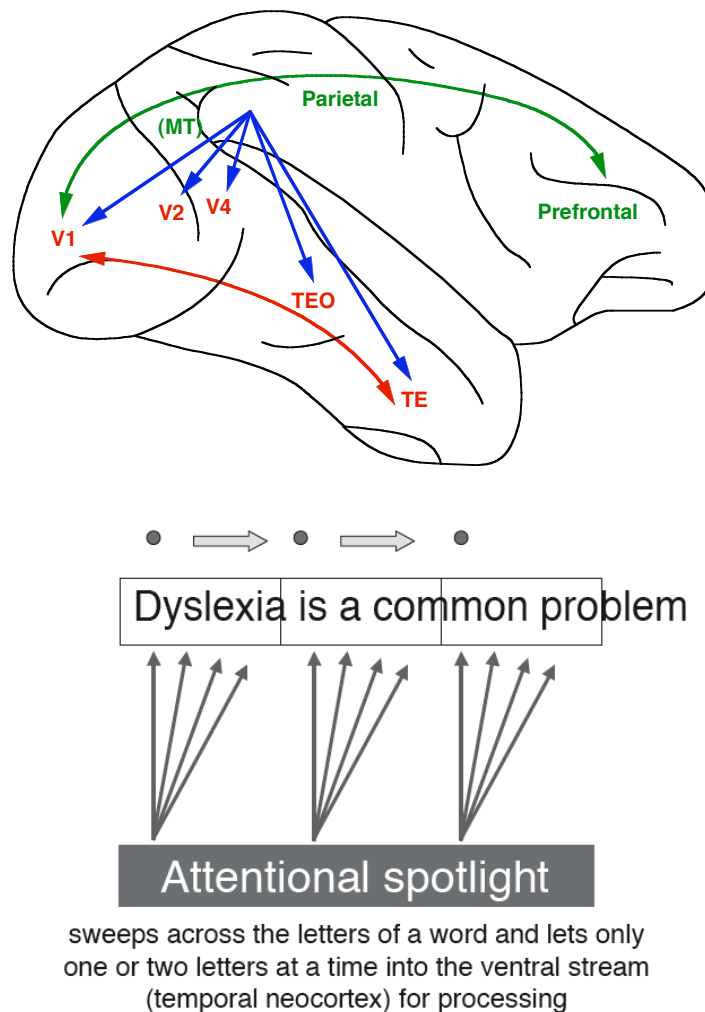


Figure 1.10: *Vidyasagar's (1999, 2001, 2004) model of visual attention. The top part (redrawn from Vidyasagar, 1999) illustrates the model of attentional spotlight. The visual information coming into the primary visual cortex (V1) is channeled into a dorsal, parietal stream carrying mostly magnocellular inputs and a ventral, temporal stream which is the major pathway for the parvocellular inputs. The attentional spotlight originating in the dorsal stream is directed at the ventral stream for enabling visual search and binding. The bottom part (reprint from Vidyasagar, 2004) is a schematic representation of the putative role of the attentional spotlight in reading. The top row shows how eye movements are executed during reading. During the fixations, seven to eight letters, represented by boxes, are classically processed. It is proposed that the attentional spotlight shifts the focus of attention from one letter to another during the fixation period, thus allowing only one or two letters to be processed at any one time.*

put, information in the dorsal stream is processed pre-attentively, that is, in parallel over the whole visual field. The information thus extracted about object locations can then be used for spotlighting purposes. Such spatial selection would obviate the need to process information over the whole visual field in the ventral stream. It would also solve the binding problem, since at any one instant only the features that belong to a single object will gain access to the higher areas for processing.” In this model, the faster M input acts as a gate for parvocellular inputs (see Figure 1.10). In reading, Vidyasagar suggested that the individual letters are sequentially processed. The dorsal stream may be necessary for the smooth flow of attentional focus that helps in the binding of the letters’ constituent features, required for the identification of individual letters or words⁸. Moreover, the sequential attentional processing may be required for the coding of letter positions. It should finally be noted that Pammer and Vidyasagar (2005) proposed a speculative account on how visual and auditory impairments may be related in dyslexia.

More recently, Facoetti et al. (2006) suggested a specific link between focusing of visuo-spatial attention and the ability to read via the analytical procedure, which is crucial for novel word reading. They grounded their claim on the observation that (i) only a sub-group of dyslexics exhibiting pseudo-word reading difficulties also showed an impaired cue-effect in a basic attentional task and (ii) the attentional score was significantly related to pseudo-word reading scores (see also Buchholz & Aimola Davies, 2005, 2006). Following Facoetti et al., pseudo-word reading requires a serial left-to-right allocation of covert attention across the letter string to realise *graphemic parsing*, that is the segmentation of a letter string into its letter constituents (for computational implementations emphasising the role of visual attention in pseudo-word reading, see Ans et al., 1998 and Perry, Ziegler, & Zorzi, 2007; see e.g. Cohen, Dehaene, Vinckier, Jobert, & Montavont, 2007 and Valdois et al., 2006 for behavioural and neurofunctional evidence). They suggest that an attentional deficit may impair graphemic parsing, which could affect all subsequent spelling-to-sound conversion processes. While being promising, this new proposal requires further empirical data.

How to precisely link visual attention to reading is not obvious. The different theoretical accounts remain largely speculative. Both models consider the visual attention impairment as resulting from the impact of a magnocellular visual defect on the (right) parietal lobe. The posterior

⁸Vidyasagar’s theory heavily rely on the feature integration theory (FIT: Treisman & Gelade, 1980; for a review, see Quinlan, 2003), in which focused attention is required for binding the otherwise free-floating features of an object.

parietal cortex, which receives predominant input from the magnocellular pathway, play indeed a key role in spatial attention (for reviews, see [Corbetta & Shulman, 2002](#); [Gottlieb, 2007](#); [Kanwisher & Wojciulik, 2000](#); [Marois & Ivanoff, 2005](#)). However, the hypothesis of a parietal impairment remains speculative, due to the lack of neurophysiological evidence in dyslexic people realising attentional tasks. Moreover, the connection with a magnocellular problem is controversial. In addition to debated anatomical and physiological data (see Section on the magnocellular hypothesis), basic behavioural evidence is at best inconclusive. Only a few studies have investigated the co-occurrence of those two deficits. In support of this view, [Iles et al. \(2000\)](#) showed that a visual search impairment was restricted to a sub-group of dyslexics with elevated motion coherence threshold, interpreted by the authors as a sign of a magnocellular defect. However, other studies failed to find conclusive evidence. [Roach and Hogben \(2004\)](#) reported a spatial cueing deficit in five dyslexic adults that did not differ from control subjects on flicker contrast sensitivity and global dot motion thresholds. The larger group of 37 dyslexic adults studied by [Roach and Hogben \(2007\)](#) was comparable to normal controls for contrasts sensitivity, but presented elevated global dot motion thresholds, in addition to impaired attentional filtering. Finally, there is a global lack of evidence in support of the proposal, made by [Vidyasagar \(1999\)](#), that word recognition requires a sequential shift of the attentional spotlight in order to encode the relative position of the word's constituent letters ([Skottun & Skoyles, 2006a](#)). Also, the ability to read single words is intact in patients with massive, bilateral damage to the parietal lobes, indicating that deployment of attention is not necessary for letter-position encoding ([Vinckier et al., 2006](#); see also [Cohen et al., 2007](#); but see [Pammer, Hansen, Holliday, & Cornelissen, 2006](#)).

To summarise, there is a large amount of evidence demonstrating specific visual attentional deficiencies in dyslexia, that are not related to a general visual or attentional impairment (e.g. [Bednarek et al., 2004](#); [Shovman & Ahissar, 2006](#)). However, the precise nature of these attentional deficits is not well understood. Only a few studies have attempted to provide empirical data linking an attentional deficit to specific aspects of reading performance. Moreover, we lack a robust theoretical framework within which understanding the way visual attention specifically affect reading acquisition.

1.4 Conclusion

Reading implies linking together a visual orthographical input with the corresponding phonological output. The vast majority of studies in the past thirty years have demonstrated the crucial importance of phonological processing in normal and abnormal reading development. This has led some researchers to consider a phonological impairment as the unique core deficit in dyslexia. Recent research has nevertheless highlighted numerous (and not fully understood) deficits in other areas, such as specific aspects of visual perception and attention. In the visual domain, the proposal of a magnocellular defect has been made, but remains controversial. The visual deficits observed are extremely complex and seem to hardly depend on fine and particular experimental conditions, which are not fully determined. Also, while the initial studies considered the dyslexic population as an homogeneous group, more recent investigations have suggested that visual impairments may be present in only a sub-group of dyslexics. The same conclusions stem from visual attentional investigations. Impairments of different visual attention components were described: sluggish focusing and engagement/disengagement, automatic orienting problems, and a particular diffuse or imbalanced mode, regularly linked to a mini-neglect syndrome. However, the precise relationships between these visual and attentional defects, on one hand, and reading acquisition on the other hand, are not known. Most causative proposals remain largely speculative or untested, and are compatible with a core phonological deficit. Otherwise stated, theses studies congruently suggest that visual and attentional processing deficiencies are associated with dyslexia. However, whether their relation to reading is causal or simply correlational remains largely unknown. Further research is thus required to bridge the gap between basic visual and attentional tasks, and reading words.

Chapter 2

Pre-orthographical constraints in reading and multi-element processing in dyslexia

The difficulty to link visual perception and attention deficiencies to the reading impairments observed in dyslexic people may partly stem from the fact that visual and attentional functions are generally investigated for their own, and not in connection to reading mechanisms. Indeed, most visual and attentional studies relied on non-verbal tasks. The advantage of such tasks is to avoid confounding effects due to the linguistic components inherent in reading. However, the use of non-verbal tasks raises a number of questions: when evidence for visual or attentional disorders comes from tasks of indirect relevance for reading (i.e., which differ grossly from the reading situation), one can question how the observed differences would influence reading. Reversely, when no disorder is found on such tasks, one cannot rule out the possibility that some more subtle visual or attentional processes are involved in reading which might be impaired in dyslexic individuals¹. Recent research suggested that investigating (multi-) letter processing might shed new light on the interplay between vision, attention, and word recognition.

¹For a similar argumentation regarding eye movements studies in dyslexia, see [Prado, Dubois, and Valdois \(2007\)](#).

2.1 Reading and visual processing of letters

Letter recognition is a key component of the perceptual front end of reading. Pelli, Farell, and Moore-Page (2003) demonstrated that the basic visual unit in word recognition is no larger than a letter. They estimated energy² thresholds to accurately identify a letter or a word of various length (2–16 letters) embedded in white noise and compared performance by pitting the human against an ideal observer model³. In their study, the ideal observer was designed to recognise words as wholes. The model required the same amount of energy to identify words, whatever their length. Contrarily, the *efficiency* of human recognition (that is the ratio of the ideal’s threshold energy to the human observer’s) was inversely proportional to word length. Efficiency for n -letter words was $1/n$ that for single letters (this phenomenon is illustrated in Figure 2.1). In other words, the visual information available to accurately identify the word’s constituent letters strictly limits single word recognition. Human performance in visual word recognition never exceeds that attainable by strictly letter- or feature-based models. Letter is thus the basic perceptual unit in visual word recognition. Pelli and Tillman (2007) further investigate the respective contributions of letter, word-shape and sentence contextual information to reading speed. They independently knock out each source of information by modifying various characteristics of the text: substituting visually similar letters, alternating case, and scrambling the order of words. Confirming a crucial role for letters, letter recognition accounts for the largest part (62%) of adult rapid serial visual presentation (RSVP) and text reading rate, independently of word-shape and sentence contextual information.

Spatial and temporal properties of letter recognition were causally linked to RSVP and text reading speed by Legge, Mansfield, and Chung (2001), through the concept of *visual span*. According to O’Regan, Lévy-Schoen, and Jacobs (1983), Legge et al. conceived the visual span as the region around fixation within which characters of a given size can be resolved. They proposed that the visual span, which is a bottom-up sensory limitation on the number of letters that can be recognised without

²In general, contrast energy is the integral of the squared signal contrast over the extent of the stimulus. The contrast energy for a letter or a word is computed as the product of squared contrast and “ink” area.

³An ideal observer is an algorithm that yields the best possible performance in a specified task, given a set of constraints on the available input information. The ideal observer is not intended to be a realistic model of what happens in human subjects. However, it provides an index of the performance that can be achieved when all the available information is used in an optimal fashion.

h		other
u		great
y	those	house
o	state	years
z	three	still
b	could	under
v	right	there
p	never	after
s	since	world

Figure 2.1: *Illustration of the proportional relation between contrast energy and length. The letter on the left has the same contrast energy (but 5 the contrast) as the (invisible) middle word. And it has the same contrast (but 1/5 the energy) as the word on the right. Note that the letter (left) is much more readable than the word (middle) with equal contrast energy and is equally readable as the word (right) with equal contrast. This is consistent with recognition by parts, and inconsistent with recognition as wholes. Reprint from [Pelli et al. \(2003, additional material\)](#).*

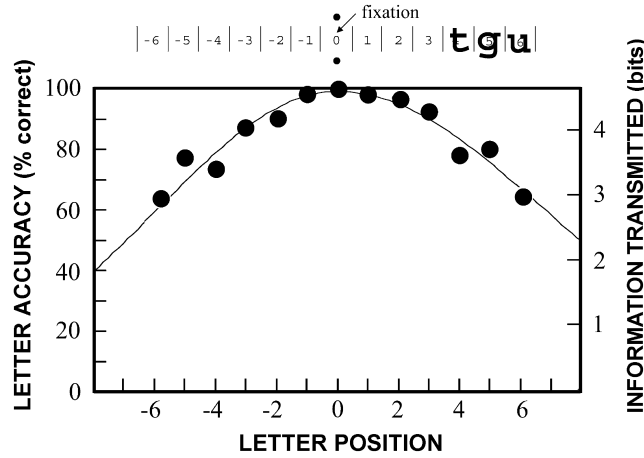


Figure 2.2: Typical visual span profiles. Top: trials consist of the presentation of trigrams, random strings of three letters, displayed at various horizontal eccentricities, defined in letter positions relative to fixation. Bottom: Example of a visual-span profile, in which letter recognition accuracy (% correct) is plotted as a function of letter position. The right axis represents a transformation in information transmitted (in bits). Reprint from *Kwon et al. (2007)*.

moving the eyes, imposes a limitation on reading speed⁴. The boundaries of the visual span are jointly determined by physical characteristics of letters, and their spatial layout. Recent work by *Pelli et al. (2007)* made a compelling case for the role of crowding⁵ in determining the visual span. *Legge et al. (2001)* further showed a temporal dependence of the size of the visual span. They estimated visual span profiles by measuring letter recognition in trigrams (that is random sequences of three letters,

⁴Note that other spans were also proposed to link visual information extraction and reading. The most influential span is without doubt the *perceptual span* (*McConkie & Rayner, 1975*) and its sub-region, the *word identification span* (for a review, see *Rayner, 1998*). Operationally, the word identification span is defined as the area around fixation from which useful identification is *effectively* extracted in order to identify words during a single fixation, while the perceptual span includes also detection of other elements such as spaces and global word form. Contrary to the visual span, which is essentially determined by sensory limitations, the size of the perceptual span (and its sub-region dedicated to word recognition, the word identification span) depends on factors in addition to letter recognition (e.g. linguistic knowledge, text difficulty). Consequently, the reduced perceptual span often observed in dyslexic people (*Rayner, Murphy, Henderson, & Pollatsek, 1989*), has been typically interpreted as a consequence of their reading deficit, rather than reflecting a less effective visual information processing. Because our work deals essentially with pre-orthographical constraints, these concepts will not be further discussed.

⁵Crowding corresponds to impaired identification of an object in the peripheral visual field by nearby elements (*Bouma, 1970*; for a review, see *Levi, 2008*).

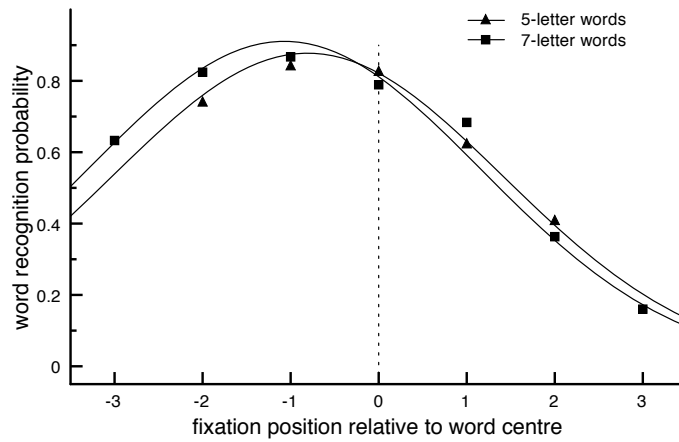


Figure 2.3: Typical viewing position effect curves. Plot of word recognition accuracy in function of the fixation position, relative to the word's center. Subjects were 7th Grade normal readers. As in adult subjects, no length effect is observed. Empirical data was fitted with Gaussian curves. Modified from [Dubois et al. \(2007\)](#).

formatted as in text) and expressed the available letter information in bits (see Figure 2.2). In adult normal readers, maximal letter identification performance is reached at fixation in 100 ms or less. However, the width of the visual span increases more slowly and requires longer exposure durations to reach asymptotic performance. In their seminal study, [Legge et al. \(2001\)](#) accurately predict adult RSVP reading rates by providing an ideal observer model instantiating a basic lexical matching rule with human visual span profiles. Further studies from the same team demonstrated an invariant relationship between reading speed and the visual span size in regard to visual modifications, such as visual eccentricity ([Legge et al., 2001](#)), letter spacing ([Yu, Cheung, Legge, & Chung, 2007](#)), as well as contrast and character-size ([Legge et al., 2007](#)).

[Aghababian and Nazir \(2000\)](#) further emphasised the importance of visual components in learning to read. They investigated the development of word recognition by means of the *Viewing Position Effect* ([O'Regan, Lévy-Schoen, Pynte, & Brugailière, 1984](#); for a review, see [Brysbaert & Nazir, 2005](#)), a systematic variation of recognition performance in function of the eyes fixation position within the word (see Figure 2.3). With only one fixation in the word, there is a position where recognition is optimal. In languages read from left to right, this optimal viewing position is located slightly left from the word centre.

Performance decreases when the eyes deviate from this optimal position, thus, producing an inverted U-shaped function. However, performance varies with fixation position in an asymmetrical way: words are better processed when fixating their initial than final letters (Brysbaert, Vitu, & Schroyens, 1996; McConkie, Kerr, Reddix, Zola, & Jacobs, 1989; Nazir, Heller, & Sussmann, 1992; Nazir, Jacobs, & O'Regan, 1998; Nazir, O'Regan, & Jacobs, 1991; O'Regan & Jacobs, 1992; O'Regan & Lévy-Schoen, 1987; O'Regan et al., 1984). Contrary to skilled readers, a word length effect was observed in learning to read children on their viewing position curves, and progressively vanishes with reading acquisition. Aghababian and Nazir (2000) suggested that this length effect might reflect the optimisation of visual information extraction. The length effect, while relatively small in comparison to 1st Grade children, nevertheless remains present at least up to the 5th Grade, indicating the importance of reading experience in optimising visual information extraction from print. More direct evidence for the involvement of visual processing in children's reading development was obtained by O'Brien, Mansfield, and Legge (2005). They observed that the critical print size—the smallest print size at which fast, fluent reading is possible—decreases with increasing age. The size of the visual span also increases with reading acquisition (Kwon et al., 2007).

Thus, despite that much is to be learned on the precise mechanisms of letter identification (Pelli, Burns, Farell, & Moore-Page, 2006), the empirical evidence briefly summarised above strongly suggests that reading is constrained by pre-orthographical factors in the visual pathway, mainly related to letter in string processing. As such, investigating visual and attentional processing of (multi-) letters may stem a good start to bridge the gap between visual and attentional impairments on one side, and reading deficiencies on the other side.

2.2 Pre-orthographical constraints in dyslexia

Recent research has highlighted the need for a better understanding of visual letter processing in dyslexia (e.g. Brunsdon, Coltheart, & Nickels, 2006). Whitney and Cornelissen (2005) suggested that dyslexia may stem from a non-optimal visual information extraction from letters in strings. Their hypothesis is grounded in the SERIOL model of reading (Whitney, 2001). This model specifies how an abstract letter-position coding scheme is extracted from print and further used to activate lexical information. The basic architecture of the model is depicted in Figure 2.4. A key assumption of the model is the serial encoding of let-

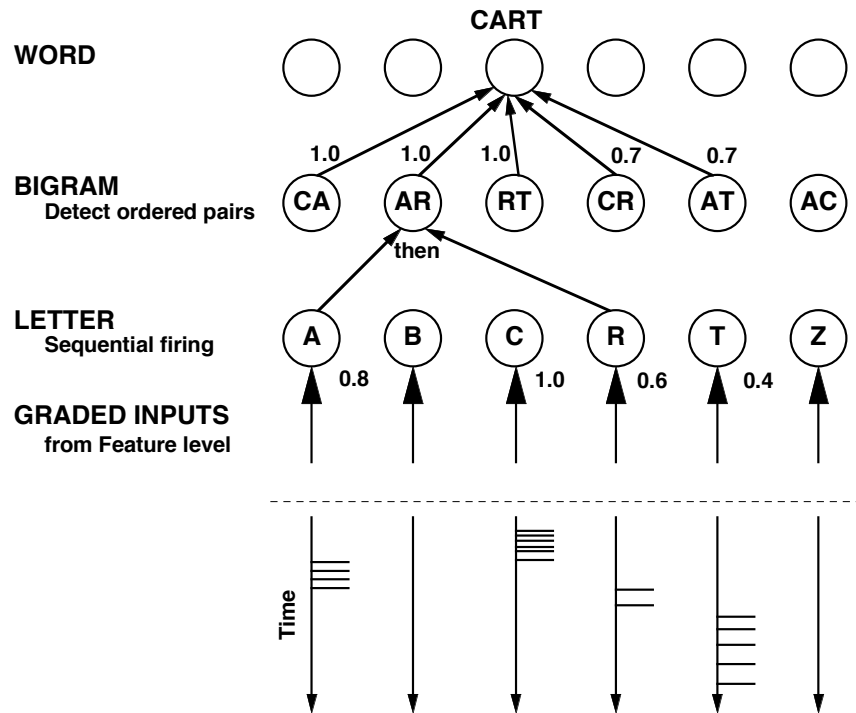


Figure 2.4: Architecture of the letter, bigram and word levels of the *SERIOL* model, with example of encoding the word *CART*. At the letter level, simultaneous graded inputs are converted into serial firing, as indicated by the timing of firing displayed under the letter nodes. Bigram nodes recognise temporally ordered pairs of letters (connections shown for a single bigram). Bigram activations (shown above the nodes) decrease with increasing temporal separation of the constituent letters. Activation of word nodes is based on the conventional dot-product model. Redrawn from [Whitney \(2001\)](#).

ter order by means of a left-to-right activation gradient input on letter nodes. In this framework, becoming a proficient reader requires the acquisition of this left-to-right gradient. [Whitney and Cornelissen \(2005\)](#) hypothesised different visual strategies, depending on the acquisition of linkages between graphemes and groups of phonetic features (what they called *graphonemes*) and optimisation of visual information extraction. At the earliest stage of reading acquisition, the reader fixates each letter and applies conversion rules. With the progressive automation of grapho-phonemic conversions, all letters will progressively fire in quick succession when fixating the first letter of the word. However, due to decreasing visual acuity, fixating the first letter limits the visibility of letters at the end of the word. Therefore, following these authors, the pre-proficient reader has to learn to fixate near the centre of the word and invoke a locational gradient (first by attentional control, then progressively becoming a bottom-up activation gradient) in order to maintain the sequential order of the letters. Moreover, [Whitney and Cornelissen \(2005\)](#) point out difficulties in acquiring this complex position encoding mechanism as a potential source of developmental dyslexia.

[Aghababian, Nazir, Lançon, and Tardy \(2001\)](#) used the viewing position effect to investigate the visual information extraction in single word recognition in a deaf beginning reader, AH. Contrary to the classical inverted-U-shaped curves (see Figure 2.3), observed after a few months of learning to read ([Aghababian & Nazir, 2000](#)), AH’s word recognition performance exhibited complete independence of the viewing position, resulting in a flat curve. Authors interpreted this result as AH’s reliance on a “logographic” strategy, in which the identity of the printed word is inferred by the help of salient visual features. Interestingly, a viewing position effect appeared fifteen months later, after successful remediation. [Aghababian and Nazir \(2000\)](#) also reported particular viewing position profiles in a German dyslexic children group and in poor beginning readers⁶, suggesting abnormalities in visual information extraction (see also [Ducrot, Lété, Sprenger-Charolles, Pynte, & Billard, 2003](#)).

In close connection to [Whitney & Cornelissen’s \(2005\)](#) hypothesis of potential problems of visual information extraction in dyslexia, [Pammer, Lavis, Hansen, and Cornelissen \(2004\)](#) investigated the sensitivity to relative position in strings in dyslexic and normal reading children. To minimize linguistic contributions, letter-like unfamiliar symbols were used in a two-alternatives forced choice task (see Figure 2.5). Participants were asked to pick which of the two alternatives they had just been shown;

⁶Unfortunately, the groups were not described and no statistical analysis was reported. The available data was restricted to plots of average group performance.

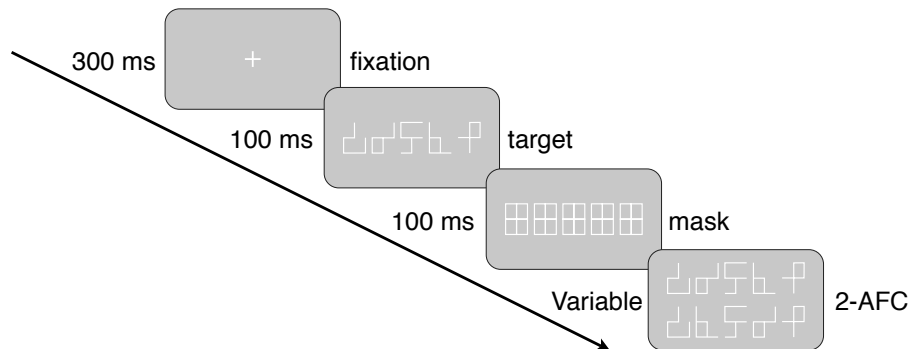


Figure 2.5: Schematic illustration of the symbol-string task used by Pammer, Lavis, Hansen, and Cornelissen (2004; see also Pammer, Lavis, & Cornelissen, 2004; Pammer et al., 2005). 2-AFC stems for two-alternatives forced choice. Modified from Pammer et al. (2005).

one was the same string, and the other was a string with the same symbols, but arranged in a different order. Dyslexic children showed lower sensitivity (d -prime) scores than control subjects when having to choose a target symbol-string among very similar strings which only differed in symbol order. Individual variation in symbol-strings sensitivity accounted for a significant amount of reading performance variance in both children (Pammer, Lavis, & Cornelissen, 2004; Pammer, Lavis, Hansen, & Cornelissen, 2004) and adult normal readers (Pammer et al., 2005), after partialling out effects of age, intellectual achievement, phonological skills, rapid automatized naming performance, and attentional dwell time. These results further suggest a link between pre-orthographic visual processing ability and visual word recognition.

Accordingly, difficulties in processing multi-element strings have recently been documented in dyslexic people (Bosse, Tainturier, & Valdois, 2007; Hawelka, Huber, & Wimmer, 2006; Hawelka & Wimmer, 2005; Valdois et al., 2003). Most of the evidence for a multi-element processing deficit in dyslexic participants was obtained by means of whole and partial report tasks of letters or digits. First introduced by G. Sperling (1960; see also Averbach & Coriell, 1961; Averbach & Sperling, 1968), whole and partial report paradigms are measures of information extraction from brief visual displays. In whole report, the task is to report the identity of as many stimuli as possible from a briefly visually displayed array. Typically, unrelated letters are presented and both the number of displayed stimuli and the exposure duration are varied. In partial report, the stimuli are divided into two classes: targets and dis-

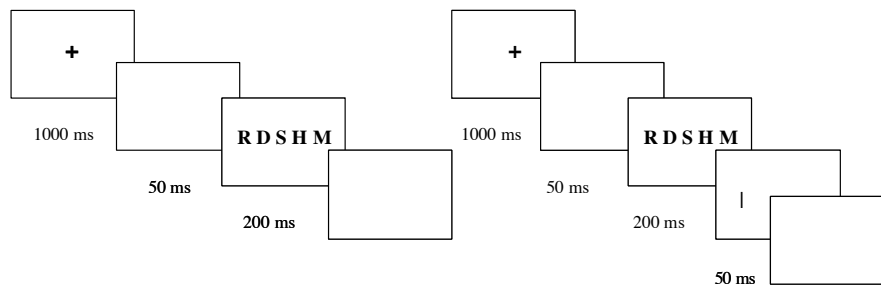


Figure 2.6: Schematic illustration of the whole and partial report tasks used by Valdois et al. (2003; see also Bosse et al., 2007; Prado et al., 2007; Valdois et al., 2004). The whole report paradigm is depicted on the left, and the partial report on the right. In partial report, the target is cued by a small vertical bar appearing below the position previously occupied by the target. Reprint from Prado (2007).

tractors. The task is to report as many of the target stimuli as possible while ignoring the distractors.

Evidence for a multi-element string processing deficit in dyslexic children was obtained in a series of experiments from Valdois and co-workers (Bosse et al., 2007; Valdois et al., 2003, 2004). In these experiments, arrays of five consonants were shown to the participants for a fixed exposure duration of 200 ms, under whole and partial report conditions (see Figure 2.6). As the stimuli were unpronounceable strings of consonants, their processing does not rely on lexical knowledge. Valdois et al. (2003) reported two contrasted cases of developmental dyslexia. Dyslexic participants were closely matched for chronological age, reading level, and intellectual achievement. A strong impairment on report tasks was observed in Nicolas, a French surface dyslexic teenager. Interestingly, the deficit remained significant when compared to younger reading age matched controls, attesting that it could not simply be due to Nicolas' reading level. On the contrary, Laurent, a phonological dyslexic boy, exhibited perfectly normal report performance but impaired phonological processing. More recently, the same tasks were presented to two large samples of French and English dyslexic children (Bosse et al., 2007). Participants were further submitted to a comprehensive reading and phonological test battery. A similar pattern of results emerged from both groups of French and English dyslexic children. As a whole, dyslexic patients reported less letters on average than chronological age matched control subjects on whole and partial report conditions. Using the factorial scores derived from a principal components analysis, Bosse et al.

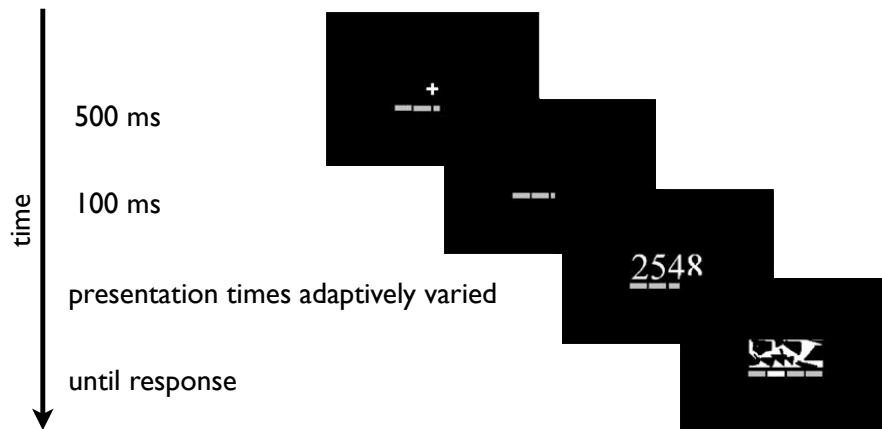


Figure 2.7: Schematic illustration of the partial report procedure used by [Hawelka and Wimmer \(2005\)](#). Reprint from [Hawelka and Wimmer \(2005\)](#).

(2007) found that both the phonological and visual multi-element processing skills were significant and independent predictors of the dyslexic children reading scores. Report tasks scores accounted for a substantial amount of unique variance in irregular word and pseudo-word reading, independently of phonological skills. In addition, [Prado, Dubois, and Valdois \(2007\)](#) reported significant negative correlations between report scores and the number of rightward fixations in text reading in a group of French dyslexic teenagers without obvious phonological problems.

Similar results were described by [Hawelka & Wimmer \(2005; see also Hawelka et al., 2006\)](#), with a partial report task (see Figure 2.7). In their studies, participants were required to identify a single element in response to a position cue after brief presentation of either digit or letter strings. The exposure duration was systematically varied in a staircase fashion in order to measure an identification time threshold, the exposure duration required for the dyslexic participants to identify target items according to a given accuracy criterion. While dyslexic children and control group mean thresholds did not differ for 2-digit strings, dyslexic patients needed significantly longer exposure durations than control subjects for longer (4- and 6-) digit strings. Furthermore, a substantial correlation was reported between the dyslexic participants' number of eye movements in single word and pseudo-word reading and their ability to process multi-element arrays, independently from pseudo-word repetition and rapid naming. A deficit in processing simultaneously displayed letters was also observed in dyslexic people using a non-verbal change detection task ([Rutkowski et al., 2003](#)).

All these findings suggest that pre-orthographical visual processing is impaired in some dyslexic individuals. Results point to a deficit in processing simultaneously displayed elements, which is related to reading performance independently of metaphonological factors.

2.3 The visual attention span hypothesis

The relation between the observed pre-orthographical deficits in dyslexia and their reading performance remains largely unexplained. A specific hypothesis has been recently proposed by Valdois and co-workers (Bosse et al., 2007; Valdois et al., 2003, 2004). Following Valdois et al. (2004), multi-element processing difficulties observed in dyslexic individuals might reflect a limitation in the amount of distinct visual elements that can be simultaneously extracted from a multi-element array and are available for further processing in reading. These authors argue that such a deficit, called by Bosse et al. (2007) the *visual attention span* hypothesis, might be a second core deficit in dyslexia, independent of the phonological deficit. Bosse et al. (2007, p. 198) defined the visual attention span as “the amount of distinct visual elements which can be processed in parallel in a multi-element array”. When reading words, this visual attention span refers to the number of the word’s orthographical units that can be identified during a fixation. However, it has been hypothesised that the visual span constraints more generally limit the simultaneous processing of multiple elements, irrespectively of their nature. Evidence for reduced multi-element processing in dyslexia, reviewed in the previous section, was observed with unrelated letters, digits, and letter-like unfamiliar symbols.

The notion of the visual attention span and its role in reading is theoretically grounded in the multi-trace memory model for polysyllabic word reading, proposed by Ans, Carbonnel, and Valdois (1998, hereafter ACV98). A key component of ACV98 is a focal processing window, called the visual attention window, through which information from the orthographic input is extracted (for similar ideas, see LaBerge & Brown, 1989; LaBerge & Samuels, 1974; see also Perry et al., 2007).

The model, outlined in Figure 2.8, postulates that reading relies on two types of reading procedures, global versus analytic, that differ in the kind of visual attentional and phonological processing they involve. First, the two reading procedures differ in the size of the focal processing window through which information from the orthographic input is extracted. In global reading mode, the window extends over the whole sequence of the input letter-string whereas the window narrows down to

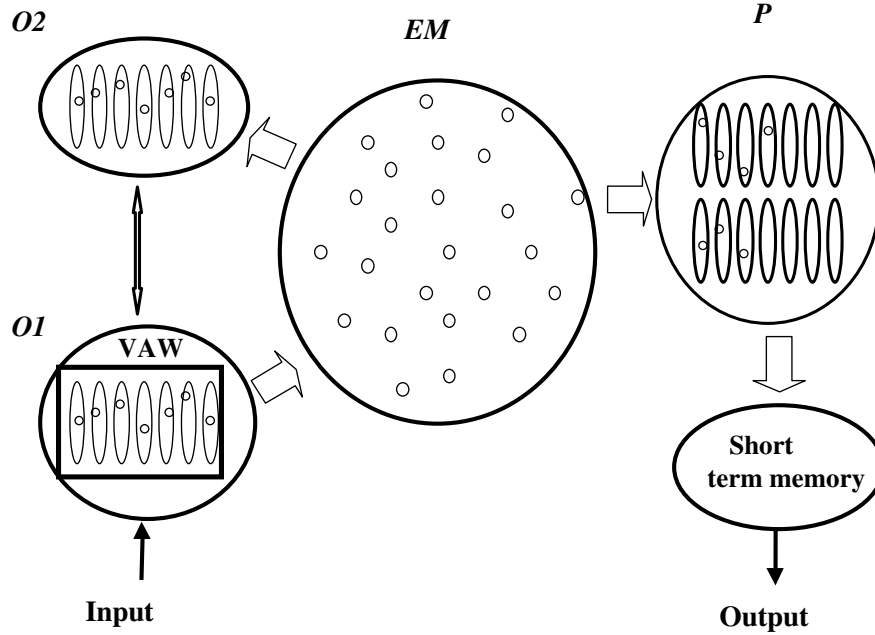


Figure 2.8: Schematic architecture of the multi-trace memory model for polysyllabic word reading (Ans et al., 1998). O1: input orthographic layer; O2: orthographic echo layer; EM: episodic memory; P: output phonological layer; VAW: visual attentional window. The phonological and orthographic layers are sets of unconnected clusters of elementary units coding for phonemes and alphabetic characters respectively. The arrows depict fully distributed modifiable connections. The double arrow symbolises a matching check procedure comparing the identity of the orthographic echo generated over O2 with the O1 input pattern. Units within the visual attentional window are maximally and equally activated. Reprint from Bosse et al. (2007).

focus attention successively on different parts of the input when reading in analytic mode. Second, the two reading procedures also differ with respect to phonological processing. In global mode, the entire phonological output is generated in a single step. In analytic mode, phonological outputs corresponding to each focal sequence (i.e., letters within the focal processing window) are successively generated and have to be maintained in short-term memory in order to remain available at the end of processing. Although the two procedures are not a priori dedicated to the processing of a particular type of letter string (real word vs. pseudo-word), most familiar words are processed as a whole by the network, whereas global processing typically fails for pseudo-words which are then processed analytically. The network was tested for its ability

to account for skilled reading and acquired dyslexia following specific damage (Juphard, Carbonnel, & Valdois, 2004; Valdois et al., 2006). Ans et al. (1998) demonstrated that a moderate reduction of the size of the focal processing window prevents reading in global mode. This reduction simulated an acquired surface dyslexia profile with a selective disruption of irregular word reading giving rise to regularisation errors. Performance was more severely impaired following a more severe reduction of the window. Irregular words continued to be the most affected class of items, but the number of errors increased on both regular words and pseudo-words. In contrast, acquired phonological dyslexia was interpreted as resulting from an independent disorder affecting phonological processing. ACV98 thus offers a theoretical framework for a possible causal relation between the number of letters simultaneously processed and proficient reading.

While ACV98 focused on simulating skilled reading and acquired disorders, the model suggests that a selective reduction of the focal processing window through which information from the orthographic input is extracted might also impact reading acquisition. More specifically, such a reduction will result in difficulties to acquire specific orthographic knowledge. Accordingly, Valdois et al. (2004) reviewed and discussed the evidence in favour of two distinct core deficits for developmental dyslexia: one affecting phonological processing, the other the visual attention span. Bosse et al. (2007) hypothesised that a reduction of the visual attention span size underlies the multi-element processing deficit in dyslexia. In agreement with the existence of two separate core deficits, results previously reviewed (see previous Section) showed that a multi-element processing deficit is observed independently of any phonological defect. Additionally, in Bosse et al.'s (2007) study, most dyslexic children exhibited a selective disorder, affecting either phonological (19% and 34.5%, respectively from the French and English dyslexic group) or multi-element processing (44% and 34.5%, respectively). Moreover, in the same study, a composite multi-element processing score was predictive of the reading level, independently of phonological processing skills.

However, the existence of a correlation between multi-element processing performance and reading level is not sufficient to demonstrate a causal relation. Other empirical evidence is thus required⁷. Also, the

⁷Possible demonstrations may rely on: (i) the observation of a significant multi-element deficit when compared to younger reading level matched controls (Bryant & Impey, 1986). This was indeed suggested by data from Valdois et al. (2003) and Bosse and Valdois (2003); (ii) longitudinal studies showing the predictive power of multi-element processing scores on ulterior reading achievement; and (iii) remediation studies demonstrating that a multi-element processing remediation has specific

impairments at the source of this multi-element processing deficit remain currently unknown.

2.4 Conclusion

Facing the difficulty to link visual and attentional problems observed in dyslexic people with their reading acquisition problems, we suggested that investigating the pre-orthographical processes in word recognition may constitute a good starting point. Despite that most is to be learned on the visual part of reading and word recognition, recent research has emphasised the importance of visual mechanisms leading to letter recognition. In adult readers, visual aspects of letter perception strictly constrain visual word recognition and essentially contribute to reading rate. Becoming a fluent reader requires adequate visual information extraction mechanisms. Few studies investigated those pre-orthographical constraints in dyslexic children. Amongst those, a deficit in simultaneously processing multiple elements was consistently described. It has been recently suggested that this deficit might reflect a difficulty in processing simultaneously displayed elements, the visual attention span hypothesis. Theoretically grounded in a connectionist model of expert reading, this hypothesis further suggests that some forms of reading impairments might originate in the reduced ability of simultaneous processing of multiple letters, independently of phonological skills. In agreement, phonological skills and multi-element processing were shown to dissociate within a non-negligible amount of individuals with dyslexia. However, most studies were correlational in nature and direct evidence in favour of a causal link is required. Also, the precise nature of this deficit remains unknown. Nevertheless, these results highlight the necessity of a better understanding of pre-orthographical factors in fluent reading and reading acquisition.

impact on reading performance.

Part II

Empirical studies

Chapter 3

Overview of the empirical investigations

In the theoretical part of this dissertation, we have shown that a large number of visual and attentional defects have been described in dyslexic individuals. However, the relationship between these deficits and reading difficulties remains elusive (see Chapter 1). In Chapter 2, we reviewed the growing number of recent researches emphasising the crucial role of visual information processing in reading. In normal readers, visual factors affecting letter information extraction and processing seem to set a strong constraint on reading (especially reading speed). In dyslexic individuals, most of the —small number of— studies dealing with pre-orthographical constraints highlight a deficit in processing multiple simultaneously displayed elements. This deficit is in agreement with predictions derived from the connectionist multi-trace model of reading (Ans et al., 1998). Accordingly, Valdois et al. (2003) suggested that the multi-element processing deficit observed in dyslexia might reflect a defect in the allocation of attention across letters or symbols strings, causally limiting the number of elements that can be processed in parallel during reading. These authors argue that such a deficit, called by Bosse et al. (2007) the visual attention span hypothesis, might be a second core deficit in dyslexia, independent of the phonological deficit (for a theoretical elaboration, see also Valdois et al., 2004). Taken together, these findings suggest that the slow serial reading of at least some dyslexic readers may have to do with visual information extraction and/or attentional problems in processing letter strings and not with orthographic word recognition per se.

The investigations reported in this Ph.D. dissertation attempted to explore the nature of the multi-element processing deficit in dyslexic

individuals by means of single and multiple-cases studies. To achieve this goal, we used new investigation methods, recently introduced in various areas of research (such as individual data modelling and bootstrapping methods), but which were not yet in use—to our knowledge—in the study of developmental dyslexia. Two main questions were addressed. First, do pre-orthographical factors constrain visual word recognition in dyslexia? This was the topic of the first study, described in Chapter 4. The results of this initial investigation pointed to the second main question of our dissertation: what is/are the impairment(s) at the source of the multi-element deficit observed in some dyslexic individuals? This question was investigated in two additional studies, reported in Chapters 5 and 6.

3.1 Pre-orthographical constraints and visual word recognition in dyslexia

Our first investigation deals with the possible impact of pre-orthographical factors on visual word recognition. In this chapter, we report the case of a young French-speaking surface dyslexic boy, MT. He demonstrated a strong reading and writing impairment, despite normal or above normal phonological skills. The absence of a phonological deficit, in conjunction with the production of visual errors in reading, led us to explore in greater detail MT's pre-orthographical processing in single word recognition. At the start of this study, in 2003, most of the literature reviewed in Chapter 2 was not yet published, and there were only a few evidence suggesting a possible role of pre-orthographical factors in dyslexia. Visual word recognition was assessed in MT by means of the viewing position effect, according to Aghababian and Nazir (2000), who used the same paradigm to demonstrate the importance of visual components in normal reading acquisition. Indeed, MT exhibited an uncommon viewing position effect curve. In normal readers, this effect has been shown to be mainly determined by the interplay of two different factors: visual letter recognition and lexical knowledge. As a consequence, further investigations were undertaken to determine the level from which constraints were putted on MT's visual word recognition abilities. More specifically, three different hypotheses were tested: Could top-down visual constraints on letter recognition (as captured by the visual span) explain MT's particular pattern in word recognition? Are MT's word recognition peculiarities simply related to a lack of lexical knowledge? Or should we consider a third, unknown, constraint (and, obviously, what kind of constraint)? The nature of the constraints affecting MT's visual word recognition

was investigated by means of psychophysics and data modelling, in an ideal-observer perspective. We have modified a basic model achieving visual word recognition (initially proposed by [Legge et al., 2001](#)), in such a way that the direct comparison between MT's behavioural data and the model's achievement will disentangle between the different hypotheses.

3.2 Sources of the multi-element processing deficit in dyslexia

Findings reported in Chapter 2 suggest that at least some dyslexic patients suffer from a multi-element processing deficit, which is related to their reading performance independently of metaphonological factors. Moreover, the observation of this deficit has been interpreted as supporting the visual attention span hypothesis. However, the precise nature of the multi-element deficit remains unclear. Indeed, report tasks, used to measure multi-element processing, involve various processes and components. Different — and possibly non exclusive — deficits could thus potentially account for these results. The ability to encode and maintain visual information is limited by two related processes that are capacity limited: visual attention enhances efficient targets processing and visual working memory supports the maintenance of encoded information (see e.g. [Awh, Vogel, & Oh, 2006](#)). Accordingly, performance on letter report tasks is known to be related to the processing rate of single letters, which rely upon visual attention limited resources ([Gegenfurtner & Sperling, 1993](#); [Shibuya & Bundesen, 1988](#)). A reduced processing speed might thus account for the multi-element processing deficit in dyslexia. In addition to a possible global reduction in visual processing speed, report performance might also be affected by a particular imbalance of the processing resources in dyslexic individuals. Indeed, [Hari et al. \(2001\)](#) have proposed that dyslexic readers might be affected by a left mini-neglect (see also e.g. [Buchholz & Aimola Davies, 2005](#); [Facoetti & Turatto, 2000](#); [Sireteanu et al., 2005](#)). Finally, in addition to processing limited capacities, visual working memory storage capacities also constrain the number of elements than can be reported when multiple items are displayed simultaneously (e.g. [Luck & Vogel, 1997](#); [Vogel, Woodman, & Luck, 2001](#); [Xu & Chun, 2006](#)). An impairment at this storage level may also be a plausible cause of the multi-element processing deficit observed in dyslexia. Assessing these different hypotheses was the aim of the second and third studies.

In the second study, described in Chapter 5, the letter multi-element processing of two dyslexic children was investigated, by combining psy-

chophysics with individual data modelling. Multi-element processing was investigated through a letter whole report paradigm. However, the previous findings were extended in a number of ways. First, our investigation method is theoretically grounded in a computational model: Bundesen's (1990, 1998) Theory of Visual Attention (TVA). TVA provides an integrated framework (described in Chapter 5 and in Appendix B) within which several accounts of the multi-element deficit in dyslexia can be formalised, related, and tested. Second, the various accounts were simultaneously assessed within the same task. Different aspects of the individual performance were further related to a number of model's parameters such as sensory effectiveness, processing capacity, attentional weighting and visual short-term memory capacity, most of which directly related to specific accounts.

The aims of the last study (Chapter 6) were manifold. We sought to extend the TVA based investigation of the multi-element processing to additional dyslexic children. We further aimed to address additional questions. First, are the observed deficits related to the oral report procedure used in whole report? Performance in the report task could indeed be influenced by unwanted factors, such as articulation programming, rapid activation of letter names, and reporting accuracy (Vogel et al., 2001). Based on a possible contribution of the oral answer to the report performance, the visual nature of the impaired multi-element processing has been recently questioned in dyslexic individuals (Hawelka & Wimmer, 2008; Shovman & Ahissar, 2006). This issue was addressed by measuring oral naming times for the stimuli used in the report task. In order to further investigate the nature and specificity of the multi-element processing deficit, we compared TVA parameter estimates for letter and colour patches. This comparison further bears on a specific hypothesis of the visual attention span hypothesis of dyslexia, that a similar level of impairment would be observed with all types of visual stimuli, as long as they are processed in parallel.

The different studies were written as separate articles, each with its own theoretical introduction. The first study has been published in Cognitive Neuropsychology (Dubois et al., 2007), the second is submitted (Dubois et al., submitted) and the third one is in preparation. As a consequence, there will be unavoidable redundancies between the general introduction of this dissertation and the literature reviewed in the different articles.