General discussion and conclusion

The present thesis was concerned with the possible constraints set by visual and attentional pre-orthographical factors on visual word recognition in dyslexic individuals. Although it is obvious to state that reading is a visual task, the way the characteristics of visual processing limit reading performance is currently not well understood. In addition, the investigations addressing this issue are currently few and far between. To this aim, we conducted several single-case studies and introduced new investigation methods.

Do pre-orthographical factors constrain visual word recognition in dyslexia?

In a first study, we reported the case of MT, a French dyslexic boy. 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. Following Aghababian and Nazir (2000), MT's word recognition abilities were investigated by means of the viewing position effect, a variation of the word recognition performance in function of the eyes' fixation position within the word (O'Regan et al., 1984). In comparison to age-matched control participants, MT exhibited a particular VPE profile, characterised by a inverse V-shaped curve and a strong length effect.

It is generally admitted that the characteristic VPE curve, observed in adults as well as learning-to-read children, mainly results from a combination of letter legibility (in function of eccentricity and visual hemifield) and lexical constraints. As a consequence, further investigations were underwent to determine at which level MT's visual word recognition abilities were constrained. Low-level visual factors affecting MT's letter visibility were assessed by quantifying the size of MT's visual span (O'Regan et al., 1983). However, MT's visual span profile was essentially identical to those of control subjects, when estimated in spatial and temporal conditions that matched those used for the VPE measure. This ruled out an explanation of MT's word recognition performance as simply reflecting differences in availability of visual information about letters. Finally, MT's word recognition was compared to that of a strictly letter-based model, in an ideal-observer's perspective. The model was designed to rely only on letter visibility information to predict the viewing position effect performance, without resorting on any kind of lexical knowledge (Legge et al., 2001). Performance of the model could thus be regarded as the level of performance reached when the whole visual information available on letters alone is used. Surprisingly, the model, provided with MT's letter visibility data, outperforms the patient's viewing position effect curve. This striking result highlights the existence, in MT, of a bottleneck that operates pre-orthographically, before lexical activation, and that is not related to low-level visual information affecting letter identification. Furthermore, the difference between MT's and the model's performance strongly suggests that MT does not use the whole available visual information on letter identities to recognise words. Accordingly, we hypothesised that these results can be accounted for by a reduction of the number of letters MT simultaneously processed.

Other results emphasise the importance of understanding the role of pre-orthographical factors in dyslexia. Recent evidence shows that a more general difficulty in processing multi-element strings characterise some individuals with dyslexia. This difficulty has been observed in dyslexic patients with simple tasks that do not require word —or even letter— recognition, including the (whole and partial) report of briefly displayed unrelated consonants and digit strings (Bosse et al., 2007; Hawelka et al., 2006; Hawelka & Wimmer, 2005; Valdois et al., 2003), sensitivity to position shifts within letter-like symbol strings (Pammer, Lavis, Hansen, & Cornelissen, 2004), and a non-verbal change-detection task (Rutkowski et al., 2003). These studies demonstrate that factors related to the processing of multi-element strings are related to reading speed and accuracy (Bosse et al., 2007) as well as eye movements when reading isolated words (Hawelka & Wimmer, 2005) and text (Prado, Dubois, & Valdois, 2007). However, all these studies are correlational in nature. In the first study, we approached the problem in another, complementary way. By using an ideal-observer modelling perspective, we demonstrated that pre-orthographical factors not only are related to, but also effectively constrain, visual word recognition.

Sources of the multi-element processing deficit in dyslexia

Difficulties in processing multi-element strings have thus been documented in dyslexic people (Bosse et al., 2007; Hawelka & Wimmer, 2005; Hawelka et al., 2006; Pammer, Lavis, Hansen, & Cornelissen, 2004; Prado et al., 2007; 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 (G. Sperling, 1960) of letters or digits. Following Valdois et al. (2004), these difficulties 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. However, the precise nature of this multi-element processing deficit remains largely unclear. Indeed, 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. Report performance might also be affected by a particular imbalance of the processing resources in dyslexic individuals. Accordingly, the purpose of our following studies was to investigate whether

Our investigations of the impairments at the source of the multi-element processing deficit were grounded in a "theory of visual attention" (TVA: Bundesen, 1990, 1998). TVA is a formal model of visual attention and (multi-) object recognition (for a review about formal models of visual attention, see Logan, 2004). It instantiates the "biased competition" framework, a leading conception of visual attention in cognitive neuroscience (Desimone & Duncan, 1995; Duncan et al., 1997), based on parallel, competitive processing (Rumelhart, 1970). Objects or elements in the visual field compete in parallel for access to a visual short-term memory (VSTM) with limited storage capacities, in an K-winners-take-all process. Objects in the visual field are processed in parallel, and the objects that are selected (and, therefore, can be reported) from a briefly exposed visual display are those objects whose encoding processes complete before the sensory representation of the display vanishes and before VSTM has been filled up with other objects. The resulting race amongst objects can be biased in such a way that some objects are favoured for selection, based on stimulus-driven, 'bottom-up' or intentional, 'top-down' factors. The different aspects of object recognition were captured by different parameters of the model: (i) *the visual processing speed, C*: the total number of visual elements processed per second from a given display; (ii) *the storage capacity of VSTM, K*: the maximum number of objects that can be extracted from a brief visual display, and finally (iii) *attentional weights, w_i*: the differential attentional resources allocation amongst the competing objects. The estimation of the various model parameters is allowed in individual subjects by fitting curves obtained with adequate psychophysical paradigms. The parameter values, derived from the theory, are mathematically independent, quantitative measures of visual and attentional components. As such, the methodology, successfully used with normal subjects (Bundesen, 1987; Bundesen & Harms, 1999; Finke et al., 2005; Hung et al., 2005; Shibuya & Bundesen, 1988) as well as brain damaged patients (Duncan et al., 1999, 2003; Finke, Bublak, & Zihl, 2006; Gerlach et al., 2005; Habekost & Bundesen, 2003; Habekost & Rostrup, 2006, 2007; Habekost & Starrfelt, 2006; Peers et al., 2005) and neurodegenerative diseases (Finke, Bublak, Dose, et al., 2006; Finke et al., 2007), is well suited to jointly investigate visual and attentional factors in multi-element processing in dyslexic children. In the current dissertation, TVA was used for its ability to capture important aspects of the data with separate, interpretable parameters.

In a second study, we used TVA to investigate the multi-element processing observed in two young dyslexic participants, AB and PA. Both participants were *a priori* selected to exhibit impaired performance on basic multi-element processing screening tasks. They were further submitted to a whole report of letters, and the different TVA parameters were estimated by fitting the model to individual report data. The most prominent result was a significant reduction in visual processing speed, C, for both of our dyslexic participants. In addition, the VSTM storage capacity, K, was also modestly reduced in AB. Finally, patients did not significantly differ from controls on measures of attentional allocation. These deficits were replicated in a third study, in which the multi-element processing was investigated in three dyslexic individuals with either a current letter report deficit (FA and LT) or a history of such a deficit (YC). FA and LT both exhibited a significant reduction of the speed at which they visually process letters, as well as a smaller VSTM storage capacity estimate. Despite that no significant deficit was observed for letters in YC, he nevertheless exhibited a slow processing speed. As in the second study, no sign of left mini-neglect was observed.

This third study was further designed to specifically address additional questions. It has indeed recently been suggested that the dyslexics' poor report performance might stem from sluggish activation of item names, instead of visual processing deficiencies (Hawelka & Wimmer, 2008; Shovman & Ahissar, 2006). Accordingly, we measured the time required by each participant to name the different items. Contrarily to the hypothesis of a sluggish activation of letter names, LT and YC exhibited normal naming times. However, longer naming times were observed in the last dyslexic participant, FA. Nevertheless, over the whole group of participants, the activation of item names (measured as individual items naming times) was related neither to visual processing speed, nor to VSTM capacity. We also tried to assess the specificity of this deficit for letter (or letter-like) material. For this purpose, report of colour patches was investigated in the same participants. Unfortunately, the results were inconclusive, due to a lack of statistical power and the data inability to constrain the visual short term capacity TVA parameter estimate.

Parallel vs. serial processing

Taken together, the results of these three studies point to a deficit in processing in parallel visual information (at least for letters). We interpreted MT's data as reflecting the fact that he was not able to process simultaneously all the letters within the word. Accordingly, in our our investigations of the multi-element deficit, the most consistently observed impairment was on the visual processing speed parameter, C. In TVA, C reflects the efficiency of visual pattern recognition mechanisms, which are constraints by limited resources of visual attention that operates in parallel across the visual field (Bundesen, 1990).

As reviewed in Section 1.3 (page 21), numerous visual attentional deficiencies has been reported in dyslexic individuals. Most of these researches investigated space-based components of visual attention, by means of cue-targets paradigms. Difficulties in covert orienting (Buchholz & Aimola Davies, 2005, 2006; Facoetti, Paganoni, Turatto, et al., 2000; Facoetti et al., 2001, 2003) , a slow and difficult focusing of attention yielding to impaired filtering of irrelevant elements (Facoetti, Paganoni, Turatto, et al., 2000; Facoetti et al., 2003; Roach & Hogben, 2004, 2007), as well as sluggish and asymmetric attentional allocation (Bednarek et al., 2004; Facoetti & Molteni, 2001; Facoetti, Paganoni, & Lorusso, 2000; Facoetti & Turatto, 2000; Facoetti et al., 2003, 2005; Lorusso et al., 2004; Sireteanu et al., 2005, 2006) were consistently reported. These difficulties have been integrated in different theoretical frameworks that attempted to link visual attention and reading problems in dyslexia. Vidyasagar (1999) has suggested that a smooth flow of attentional focus (dependent on the dorsal visual pathway) is required for identification of individual letters and words, by allowing the binding of the different features composing a letter and the coding of letter spatial position. In Hari and Renvall's (2001) *SAS* theory, dyslexic individuals are supposed to suffer from a sluggish attentional shifting mechanism. Due to this, the attention of dyslexic subjects, once engaged, cannot easily disengage, and vice versa. Despite important differences in the causal chain between attention impairments and reading problems, both theoretical accounts rely on a serial conception of attention. On the contrary, TVA assumes parallel processing of simultaneously presented stimuli not only at low levels of the visual system but also at high levels. Serial and parallel models crucially vary in the predicted dynamics of deploying and redirecting attention. "A typical serial model assumes that attention focuses on one object in the visual field at a time, moving about at a high speed. In contrast, a typical parallel model assumes a broad distribution of processing resources over the visual field, shifting slowly, but comprising many objects simultaneously" (Bundesen & Habekost, 2005, p. 112).

Might the impairments observed in our dyslexic participants in the letters report task in fact reflect problems in serial, rather than parallel, processing? In principle, new TVA fits on our data might help to disentangle the two hypotheses. Indeed, following TVA, all the processing capacity is devoted to the displayed objects. Accordingly, processing capacity estimates are expected to be constant across variations of the number of elements displayed[15]. On the contrary, problems in serial attention allocation might manifest in an inverse relation between processing speed and the number of displayed items (for a similar argument, see Duncan et al., 2003). Indeed, the more items, the more attentional shifts. Accordingly, new TVA fits were done for each participant, separately for each display size. Unfortunately, the ratio of number of data points to number of free parameters was not sufficiently high to allow reliable parameter estimates.

The distinction between parallel and serial processing is fundamental and has been very widely studied (for a review, see Bundesen & Habekost, 2005). However, studies targeting the issue have mostly been based on analyses of set size functions in visual search paradigms. Following Treisman and Gelade (1980), parallel processing is classically inferred from search time functions showing only minor increase with display set

[15]Formally, this proposal is only true for displays consisting of objects with the same sensory effectiveness, $s_{(x,i)}$ (defined as $\eta(x,i) * \beta_i$ in Equation B.1, in Appendix B). If it it the case, Equation B.1 imply that C is constant across variations in both the number of objects in the display and their attentional weights. Thus, when sensory effectiveness is kept constant, C may be regarded as a fixed total processing capacity divided among the different objects in the display.

size, whereas large increases of search times, linearly related to set size, were taken as reflecting serial processing. However, the strict dichotomy between fast parallel and slow serial search was not observed on the distribution of reaction times. For example, in a retrospective investigation of a large data set (including 2,500 experimental sessions and about 1,000,000 trials), Wolfe (1998) did not find the expected bimodal distribution of the search time function. This has led Bundesen et al. (2003) to introduce a new paradigm to investigate serial vs. parallel processing: the *multifeature* whole report paradigm. It is a whole report paradigm in which items are defined by two features (e.g. coloured letters) that must be reported. The rationale was as follows: if and only if processing is parallel, there must be instances for which partial information would be reported for both stimuli (e.g. the colour for an item, and the letter identity for the other) when processing is interrupted before finishing (e.g. short exposure duration, post-masked). Indeed, occurrences of partial information from both stimuli were observed, stemming against simple serial processing in whole report. Moreover, Bundesen et al. reported stochastic independence between probabilities of features report. This result was well fitted with a simple parallel-processing model assuming independent processing of features both within and between the stimuli. Results were extended and a more complicated serial model[16] was further discarded in a recent study using the same paradigm (Kyllingsbæk & Bundesen, 2007). There is thus strong indications of considering our C processing speed estimate as reflecting parallel processing of the dis-

[16]Instead of completing processing of one of the stimuli before processing of the other one, this modified serial model spent constant time on the first stimulus, regardless of whether and when the participant identifies any features of the first stimulus. In certain specific conditions, such a model would also predict stochastic independence of feature report. However, this modified serial model predicts dependence of features report for within object features in front of trial-to-trial variation o the exposure duration. On the contrary, perfect stochastic independence was observed (Kyllingsbæk & Bundesen, 2007, Experiment 2), in agreement with parallel-processing model assuming independent processing of features both within and between the stimuli. As acknowledged by Kyllingsbæk and Bundesen (2007), the serial model will nevertheless mimic the predictions of the simple parallel model if multiple rapid shifts are made between objects. Indeed, serial shifts of visual attention have recently been shown by VanRullen, Carlson, and Cavanagh (2007) in a visual search task of a small decrement of luminance amongst continuously flickering circles filled with spatiotemporal white noise. Moreover, this periodic sampling was also observed when only one location has to be monitored. VanRullen et al. argued that this sub-optimal sampling strategy might stem from intrinsic properties of our sensory systems. However, the estimate time of processing devoted to an item before shifting to another one was about 140 ms (about seven elements per second), too slow to account for whole report performance (classical maximal exposure duration below or equal to 200 ms). For a discussion of processing times and serial vs. parallel processing, see Wolfe (2003).

played items.

Our results thus point to an impairment in visual parallel processing, that, at least in MT, constrains visual word recognition. These results are in global agreement with the visual attention span hypothesis (Bosse et al., 2007; Valdois et al., 2003, 2004). According to Bosse et al. (2007, p. 198), the visual attention span is defined as "the amount of distinct visual elements which can be processed in parallel in a multi-element array". A reduction of the visual attention span "might reflect deficits in the allocation of attention across letter or symbol strings, limiting the number of elements that can be processed in parallel during reading" (p. 200). In agreement, we showed a reduction in the total visual capacity that is allocated for parallel processing of letters in our dyslexic participants. Furthermore, MT's results suggest that his visual word recognition abilities are limited by the number of letters he simultaneously processed.

However, these results also highlight the need of a better operational definition of the visual attention span. Following Valdois et al. (2003), the visual attention span has been operationally defined as performance on whole and partial report tasks. In both tasks, five consonants were displayed for a fixed exposure duration (200 ms) and without a mask. In the partial condition, the stimulus is immediately followed (ISI: 0 ms) by a spatial cue, lasting for 50 ms. Subjects are required to either report as many of the letters as possible (whole report condition) or only the post-cued letter (partial report condition). Both tasks are short and easy to administrate to large samples. For example, Bosse et al.'s (2007) study included as much as 97 dyslexic participants and 78 control subjects. However, as a counterpart, it is difficult to distinguish between the different factors that may contribute to the performance. As previously discussed, two main factors are setting limits to the number of letters that can be reported in a whole report performance: the processing speed and VSTM storage capacities. However, following the current definition of the visual attention span, only the first is of direct relevance for reading (see also below). Conversely, VSTM is usually considered to be of negligible importance to the development of reading skills. The importance of the constraints set by these two limited capacities mechanisms on report performance vary in function of the exposure duration (Shibuya & Bundesen, 1988). At short exposure durations, report performance is mainly driven by processing speed, while VSTM capacity constraints are manifest at longer exposure durations. The 200 ms exposure duration was chosen by Valdois et al. (2003) to correspond to the average fixation duration in reading. However, as such an exposure duration, average report performance is probably a mix of both constraints, in a variable proportion in different participants. Accordingly, in addition to the processing speed deficit, a small reduction of the VSTM storage capacity, K, was also observed. The behavioural significance of the smaller VSTM capacity is not straightforward. Indeed, memory capacity vary considerably across normal individuals, classically ranging from 3 to 5 (Duncan et al., 1999, 2003; Habekost & Bundesen, 2003; Vogel et al., 2001; Vogel & Machizawa, 2004; Vogel et al., 2005) and the storage reduction we observed is relatively small, well within the classical range. Nevertheless, this might result in an unwanted reduction of the visual attention span estimate.

Levels of the pre-orthographical constraints in reading

In TVA, the interpretation of the C parameter, the visual speed of processing, is two-fold (Bundesen, 1990; for a similar discussion of C interpretations in the context of neuropsychological case studies, see Duncan et al., 1999). C in a sense is a total visual processing capacity shared out among the different elements in the array. On the other hand, C is evidently a sensory parameter, dependent on such factors as discriminability, retinal eccentricity, and so on[17]. Whereas the original TVA model was framed at a cognitive description level, its principles have been shown to have a strong analogy at the single cell level (the Neural Theory of Visual Attention, NTVA: Bundesen et al., 2005). In NTVA, visual processing capacity is distributed across stimuli by dynamic remapping of receptive fields of cortical cells (Moran & Desimone, 1985). Accordingly, the total processing capacity, C, is proportional to the total activation of neurons a level of processing at which the classical receptive fields of neurons are so large that each one covers the entire stimulus display. The activation of these neurons in turn depends on the activation of neurons in lower level cortical areas (Kyllingsbæk et al., 2007). C is thus the product of a whole series of processes, starting from basic feature detection, up to object recognition. If the processing speed estimate en-

[17]The two properties follow from Equation B.1, in Appendix B. When sensory effectiveness is kept constant, C may be regarded as a fixed total processing capacity divided among the different objects in the display (see footnote 15, page 178), and the weight ratio $w_x/\sum_{z\in S} w_z$ may be regarded as that proportion of the total processing capacity C that is allocated to element x. However, when sensory effectiveness vary between elements, C reflects this variation. This is the reason why C is estimated separately for each hemifield in the case of —unilateral— brain damage, in which sensory effectiveness may be affected differentially affected across the hemifields (see e.g. Habekost & Rostrup, 2006; Peers et al., 2005).

compasses so different aspects, at which level(s) are situated the deficits responsible for reduced processing speed in our dyslexic participants? And at which level a processing speed impairment might impair reading performance?

Legge et al. (2001) proposed that the size of the visual span —the number of letters recognisable in a glance— imposes a fundamental limit on reading speed. They defined the visual span as "the number of letters that can be recognized in parallel" (p. 725), without moving the eyes and formatted as in text. The visual span, putatively limited by acuity, crowding, lateral masking, and mislocalisation of letters, represents a sensory bottleneck for reading in both adults (Legge et al., 2001, 2007; Yu et al., 2007) and learning to read children (Kwon et al., 2007). Pelli et al. (2007) reported compelling evidence that the visual span strictly corresponds to what they called the uncrowded span, that is the number of character positions in a line of text that are not crowded. They showed that reading rate is proportional to the uncrowded span. In addition, they showed that the critical spacing —i.e. the smallest distance between letters that avoids crowding— for letter identification predicts both the critical spacing and the span through which visual information is extracted for reading. There is thus strong emphasis in the literature for a key role of low-level visual factors constraining letter recognition in both normal adults and learning to read children. Are our results explained by such low-level factors? This question may turn to a semantic one. Is 'visual attention span' simply another word for 'visual span' or 'uncrowded span'?

In the first study, the impact of low level factors on MT's letter recognition was captured trough the computation of his visual span profile. With a strict matching of the display conditions (including exposure durations) between the estimation of the viewing position effect and the visual span profile, MT's visual span profile was indistinguishable from those of control subjects. However, it does not mean that MT's letter identification was completely unaffected by low-level, sensory factors. Indeed, MT's visual spans are smaller than those of skilled readers when similar exposure durations are used (data not shown in Study 1). That the model word recognition performance outperformed MT's one could nevertheless not be attributed to the a visual span reduction. The model was indeed submitted to low-level visual constraints identical to MT, by being provided with MT's own visual span profiles. Accordingly, the discrepancy between MT's word recognition performance and the model's one does not depend on low-level visual factors. In line with our explanation of the data are recent results obtained in patients suffering from age-related macular degeneration. Cheong, Legge, Lawrence, Cheung, and Ruff (2008) showed that the visual span was not related to reading in those patients. An additional factor was required to account for significant proportion of inter-individual reading rate variation: the information transfer rate, that is the amount of visual information transferred trough the visual span in a given time (see also Cheong, Legge, Lawrence, Cheung, & Ruff, 2007). In the following studies, we used a display that minimises the contribution of the factors supposed to determine the visual span. In the periphery, the isolation field (the area in which crowding occurs) has an elliptic form with a radial critical spacing (the largest one) equivalent to $\approx 0.5\times$ the target eccentricity (for a recent review on crowding, see Levi, 2008). In our experiments, the distance between the different items was equivalent to their visual eccentricity, a distance at which crowding is not expected. We conclude that (i) the abnormal difference observed between MT's word recognition performance and the model's predicted one, and (ii) the processing speed reduction are probably not accounted for by the low-level visual factors putatively affecting the visual span (crowding, acuity, positional coding).

Taken together, our results strongly suggest that the identification of multiple letters are also constrained by restricted processing resources in dyslexia. How are the deficits we observed related to reading acquisition? A possible causal link is suggested by the visual attention span hypothesis. Indeed, the visual attention span hypothesis is theoretically grounded in the multi-trace memory model of polysyllabic word reading (ACV98: Ans et al., 1998). 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 (Valdois et al., 2004). In the network, a new word memory trace is created during reading each time the entire orthographic input and the entire phonological output of the input item are simultaneously available. Accordingly, a reduction of the window through which information from the orthographic input is extracted should result in an inability to create word traces, interfering with the normal development of the global reading procedure. The model thus suggest that a inter-individual differences in this visual parallel processing mechanism might not only affect the ability to read in global mode, but also to learn orthographical knowledge. However, this hypothesis remains currently speculative, as most results only demonstrated correlations between report performance and different aspects of single word and text reading. In study 1, we tried to go one step beyond correlations, by demonstrating in MT the existence of pre-orthographical constraints in visual word recognition, that were not related to basic low-level visual factors.

There is nevertheless evidence suggesting that low level visual factors may also differentially affect reading performance in dyslexia. First of all, stronger crowding has been sometimes reported in dyslexic individuals (Bouma & Legein, 1977, 1980; Pernet et al., 2006; Spinelli et al., 2002; but see Shovman & Ahissar, 2006). Concomitant with reading acquisition is observed an increase of the visual span size (Kwon et al., 2007) and a decrease of the critical print size (O'Brien et al., 2005). In addition, dyslexic reading curves showed higher critical print sizes and shallower reading rate-by-print size slopes below the critical print size. Pelli et al. (2007) demonstrated that the shape of the reading rate-by-print size function (and consequently the critical print size) is determined by crowding in normal readers. Visual low-level factors will undoubtedly —at least partially— constrain reading in dyslexia, but their impact has not yet been investigated. As discussed above, Cheong et al. (2008) recently put the case for the combination of spatial (the visual span profile) and temporal (the information transfer rate) properties of letter recognition in understanding reading rate. Future research should thus try to clarify the interplay between the different pre-orthographical factors that may constrain reading in dyslexia.

This question is also of importance for current theories of reading and reading acquisition. Despite its importance for fluent reading, the visual 'front end' of reading has been neglected by most formal models of reading (e.g. Ans et al., 1998; Coltheart et al., 2001; Perry et al., 2007; Plaut et al., 1996; Seidenberg & McClelland, 1989). As a consequence, these models often presuppose a case- and location-invariant representation, without specifying the mechanisms achieving it. Dehaene, Cohen, Sigman, and Vinckier (2005) recently suggested that parallel letter recognition might be a natural consequence of general principles that govern the visual system. Based on the neurophysiological organisation of the ventral occipito-temporal route for object recognition (Malach, Levy, & Hasson, 2002), they proposed that increasingly broader and more abstract local combination detectors might progressively achieve invariant word recognition (see Figure 6.7). Such a hierarchical organisation has recently been found by Vinckier et al. (2007) along the (left) occipito-temporal cortex, following a posterior-anterior gradient. This framework might help in delineating different possible levels at which pre-orthographical constraints may operate. Investigating the relative contribution of pre-orthographical factors in normal and pathological reading acquisition will thus also lead to asking how the occipito-temporal cortex is progressively tuned to letter and word processing.

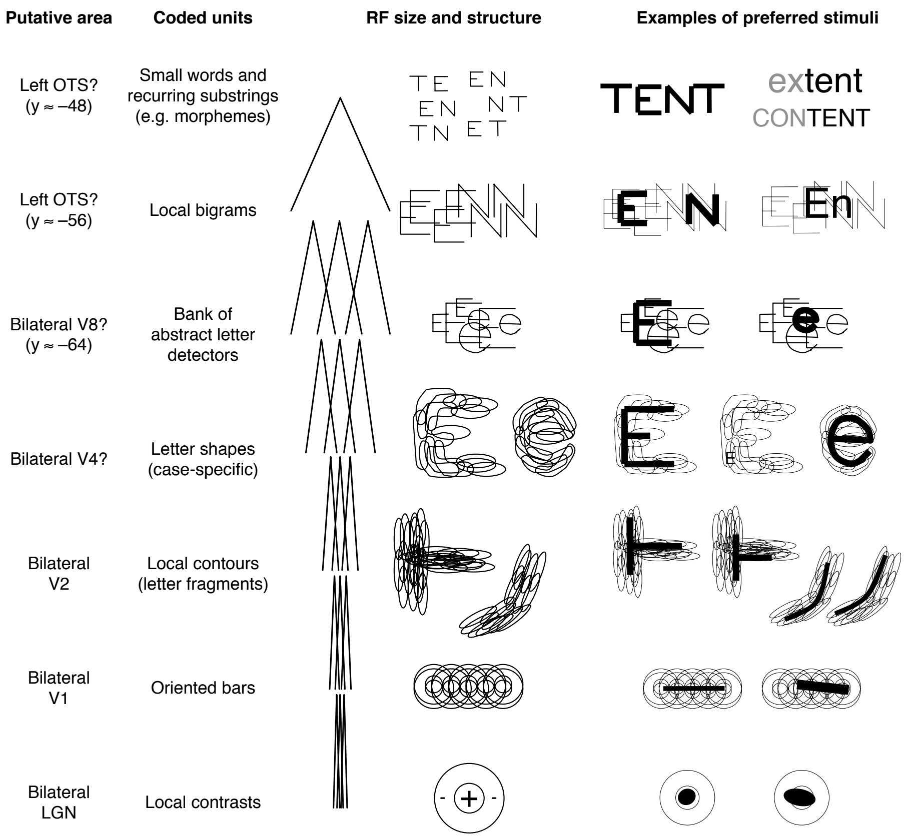

Figure 6.7: *Model of invariant word recognition by a hierarchy of local combination detectors (LCDs). Each neuron is assumed to pool activity from a subset of neurons at the immediately lower level, thus lead to an increasing complexity, invariance and size of the receptive field at each stage. Putative anatomical localizations are displayed on the left. Abbreviations: OTS, occipito-temporal sulcus; LGN, lateral geniculate nucleus; y, approximate antero-posterior coordinate relative to the human Montreal Neurological Institute template. Reprint from Dehaene et al. (2005).*

Appendices

Appendix A

Bootstrap analysis

First introduced by Efron (Efron, 1979; Efron & Tibshirani, 1993), the bootstrap is a data-based simulation method for statistical inference. The bootstrapping method relies on a resampling procedure in a computer-intensive way. It consists of creating many resamples of the same size as the original sample by repeatedly sampling *with replacement* from the original data. This way, any single observation could be drawn a random number of times from the original sample. If a statistic (such as the mean or the more complex prediction from our model) is computed from each of the numerous different bootstrap samples, a bootstrap probability distribution of that statistic is obtained. The standard deviation of the bootstrap distribution is an estimator of the variability of the sampling distribution of that statistic. When resampling is done from a single subject's data, the bootstrap distribution represents the variability introduced by the measurement error related to each intra-individual measurement. It is particularly useful when investigating deficits at a single case level, where demonstrating that a given test's result did not occur by chance is crucial (for similar use of bootstrap analysis in single case studies, see e.g. Habekost & Bundesen, 2003; Habekost & Rostrup, 2006, 2007).

For both bootstrap analyses, MT's data was resampled 10,000 times. Resampling was made with replacement. Moreover, as the bootstrap samples were provided as input to the model, resampling was done in such a way that the same number of items was obtained for each viewing condition in a given bootstrap sample. This constraint was putted to ascertain that sufficient data was drawn from each condition to obtain robust curves estimates.

Drawing confidence intervals

In the first analysis, we sampled MT's letter identification data, consisting of 450 items. Thus, each bootstrap sample included also 450*3 letters data points. Each bootstrap data set was provided as input to the model. This way, 10,000 predicted curves were obtained (each curve consisting of one probability of correct word recognition for each of the five different viewing positions). We were thus given with five different distributions of the predicted values, one for each of the five viewing positions. Percentiles 95% bootstrap confidence intervals were finally derived from these distributions by taking the empirical 0.025 and 0.975 quantiles of the bootstrap estimates distribution.

p-value of the difference

In the second analysis, we would like to incorporate measurements errors from both MT's letter identification data and word identification experiment. Moreover, we are interested in the *difference* between MT's actual VPE curve and the model's predicted one. Consequently, in each bootstrap run, two different samples were drawn, one from MT's letter identification data (as in the previous analysis) and one from his word identification data (from Exp. 1). The letter bootstrap sample was provided as input to the model. The *difference* between the curve outputted by the model and the word identification bootstrap sample was then computed for each viewing position. This way, 10,000 difference values were obtained for each viewing position, yielding to five different distributions of this difference. Finally, unilateral p-values were computed as the percentage of bootstrap estimates falling below zero (that is, the absence of difference).

Appendix B

The TVA model

General theory

TVA is a joint theory of attentional selection and visual recognition. In TVA, visual recognition and attentional selection consist in making perceptual categorisations. A perceptual categorisation has the form "x belongs to i"; where x is an element in the visual field and i is a perceptual category (such as a letter type). As an example, "the element displayed at the upper left position is a B" is a perceptual categorisation.

A given element from the visual field is selected (and simultaneously recognised) if and when a perceptual categorisation for this element enters a limited-capacity visual short-term store: the visual short-term memory (VSTM). In contrast to many serial models of attention (e.g. Treisman & Gelade, 1980), TVA is based on parallel, competitive processing (Rumelhart, 1970). Objects or elements in the visual field compete for access to the VSTM, in an K-winners-take-all process. Selection is determined by temporal characteristics of processing. Objects in the visual field can be processed in parallel, and the objects that are selected (and, therefore, can be reported) from a briefly exposed visual display are those objects whose encoding processes complete before the sensory representation of the display vanishes and before VSTM has been filled up with other objects. Competition is thus considered as a race: recognised elements are those who were processed faster.

For each element in a given display, the rate at which a particular categorisation "x belongs to i" is encoded into VSTM, $v(x, i)$, is given by Equation 1 of TVA:

$$v(x, i) = \eta(x, i)\beta_i \frac{w_x}{\sum_{z \in S} w_z} \tag{B.1}$$

where $\eta(x,i)$ is the strength of the sensory evidence that element x belongs to category i, β_i is the perceptual bias to classify any element as belonging to category i, and $w_x/\sum_{z\in S} w_z$ is the relative attentional weight allocated to element x (i.e. the weight of object x, w_x, divided by the sum of the weights across all objects in the visual display S). The ratio of attentional weights is the way by which competition between elements is "biased", based on "bottom-up" and "top-down" factors.

In most experimental set-ups, $\eta(x,i)$ and β_i values may be assumed to be constant. As a practical consequence, they can not be distinguished from each other and form a compound estimate:

$$s(x,i) = \eta(x,i)\beta_i.$$

The $s(x,i)$ parameter represents the degree of pattern match between element x and a template i in long-term memory. As a consequence, this parameter is affected by the sensory properties and general discriminability of the stimuli, but also by learning which may lead to change in or even development of new representations (For more details, see Bundesen, 1990).

Consider the case when the VSTM storage capacity exceeds the number of displayed elements. In this case, the time taken to encode x in VSTM is exponentially distributed. Specifically, the probability that element x gets encoded into VSTM at time t equals

$$P(t) = \begin{cases} 0 & \text{for } t < t_0 \\ 1 - \exp\left[-v(x,i)(t - t_0 + \mu)\right] & \text{for } t \geq t_0 \end{cases}$$

where t_0 denotes the *minimal effective exposure duration*, below which no information is extracted from the display, and μ captures the prolongation of the effective exposure duration in the case of unmasked displays. Thus, $(t - t_0 + \mu)$ is the *effective exposure duration* of the stimulus. After a minimal exposure duration, t_0, processing follows the exponential distribution with a rate parameter corresponding to $v(x,i)$. When x is displayed alone, $v(x,i)$ is the sensory effectiveness of object x, $s(x,i)$. When multiple elements are displayed, the sensory effectiveness of each element $s(x,i)$ is scaled by their relative attentional weights $w_x/\sum_{z\in S} w_z$, as expressed in Equation B.1. When more than one element is displayed, the total processing capacity C for the display could be computed as the sum of v values across all perceptual categorisations of all elements in the visual field

$$C = \sum_{x\in S}\sum_{i\in R} v(x,i)$$

where R is the set of all perceptual categorisations. Thus, C is a measure of the total rate of information uptake (in objects per second). Also, the balance between attentional weights was estimated by

$$w_{lat} = \frac{w_{left}}{w_{left} + w_{right}}$$

where w_{left} and w_{right} are the mean of the attentional weights w respectively in the left and right hemifields. As a consequence, a w_{lat} value at 0.5 indicates a symmetrical attention distribution. When the attention allocation is asymmetrical, w_{lat} deviates toward 0 (in the case of a right hemifield advantage) or 1 (in the case of a left hemifield advantage).

Matters are mathematically more complicated when the VSTM capacity K is a limiting factor. In this situation, processing times of the categorisations remains obviously exponentially distributed and are still mutually independent, but only categorisations from the first K stimuli will be encoded in VSTM. Details may be found in Kyllingsbæk (2006).

Experimental paradigms and parameters estimation

The main paradigms modelled by TVA have been whole and partial report tasks (G. Sperling, 1960, see text for details). However, the choice of the experimental settings had implications on the model's parameters that can be estimated. If the exposure duration is kept constant, it is not possible to separate v from the effective exposure duration $(t - t_0 + \mu)$. As a consequence, no pure estimation of *processing speed* is allowed. On the other hand, if the display size is kept constant, v-values can not be decomposed in sensory effectiveness s and attentional weights w. Our experimental paradigm thus involved a systematic variation of both exposure duration and set size to allow the distinction between processing speed and attentional weighting.

Before fitting the data, a decision has to be done concerning the number of parameters to be estimated. Indeed, TVA allows the fitting of various sets of parameters. Parameters K, t_0 and μ could vary from 1 to the number of experimental conditions. This is particularly useful for the study of neurological patients with unilateral lesions. In this case, experimental conditions in which stimuli are displayed unilaterally are required. Though essential in data fitting, t_0 and μ parameters were not directly linked to the various theoretical accounts of the multi-element processing deficit in dyslexia (but see Habekost & Bundesen, 2003, for a demonstration of the usefulness of the t_0 parameters in sub-clinical attentional disturbances). They were thus constrained to be identical across conditions. Also, K was shown to be highly bilateral in normal control subjects, as well as in patients with parietal (Bublak et al., 2005; Duncan et al., 1999), occipital or occipito-parietal (Duncan et al., 2003) and frontal-subcortical lesions (Habekost & Bundesen, 2003). This lead Habekost and Bundesen (2003, p. 1178) to state that "damage to VSTM is typically nonspecific, reducing capacity uniformly in the visual field" (see also Habekost & Rostrup, 2007). As a consequence, our experimental conditions did not included unilateral displays. Processing rate $s(x)$ and attentional weight $w(x)$ could vary from 1 to the number of different position in the display. Previous results emphasised that processing speed was highly correlated between the hemifields in normal subjects as well as in neglect and simultagnosic patients (Duncan et al., 1999, 2003, see also Bublak et al., 2005), thus arguing for s as constant between hemifields in dyslexic patients. However, Habekost and Rostrup (2006, 2007) recently reported a unilateral processing speed deficit in the contralesional visual hemifield of patients with anterior right hemisphere lesions. We thus fitted 6 different parametrisations to the data, resulting from the combination of 1, 2 (one for the left hemifield, one for the right) or 6 (one for each position) s-values and 2 or 6 w-values. Because we were interested in the attentional imbalance between hemifields in dyslexic patients, at least 2 different w-values were required. We then chose the best fitted model as the model that minimises the Bayesian Information Criterion (Schwarz, 1978) across the participants. The selected model includes only one s-value and six w-values, one for each possible position in the display. Data was thus best explained by a model in which processing speed is the same for the different possible positions. Interestingly this model is also the one that minimises the bootstrap *SD*s, indicating highest reliability in the individual parameter estimates.

Appendix C

Colour characterisation

	CIE *Lab*			Weber
	L	*a*	*b*	Contrast
Background				
dark grey	18.98	5.72	-8.72	-
Letters				
white	85.43	1.84	-30.37	3.50
Colour patches				
red	40.63	55.83	46.94	1.14
green	55.61	-65.63	51.09	1.93
blue	31	49.93	-80.99	0.63
yellow	66.98	-24.5	62.25	2.53
magenta	45.23	65.16	-34.85	1.38
cyan	64.58	-24.79	-36.59	2.40
orange	56.41	26.26	53.72	1.97
purple	45.53	74.82	-92.52	1.40
brown	45.55	10.87	12.28	1.40
light grey	50.37	3.17	-21.21	1.65

Note. *CIELab is a 3D space. The L dimension corresponds to lightness (in cd/m^2), whereas the a and b dimensions define a plane orthogonal to L such that the angle of a vector in that plane, rooted at the L axis, corresponds to hue and the radius of such a vector corresponds to saturation. Weber luminance contrast was computed as* $(L - L_b)/L_b$*, where L is the luminance of a given colour, and* L_b *the luminance of the background.*

Appendix D

Re-analysing the colour data

A new analysis of the data was underwent in order to estimate whether the parameter estimates were affected by guessing. TVA indeed models the probability that exactly j items enter the VSTM on a given trial. In order to measure it, subjects are instructed to report an item if and only if they are 'fairly certain' that the item was presented. The assumption is made that reported items are in fact the items that were encoded in VSTM. However, this assumption does not hold if subjects guess. As a consequence, parameter estimates may be inflated, in front of guessing.

Guessing may particularly affect the K parameter estimate. Indeed, the K estimation is bounded between the maximal number of items (here colour patches) accurately reported by the subject and this number minus one. Consequently, if a subject reports once an accurate additional item because of guessing, the range allowed for the estimation of this subject's VSTM storage capacity is shifted by one element. Outliers have thus a major impact on the K estimate. In the previous analyses, we tried to minimise the impact of guessing on K by (i) removing outliers, and (ii) constraining the bootstrap samples to contain at least one item with the subject maximal score. Outliers were defined following Duncan et al. (1999, p. 475): "A trial was considered an outlier if (a) the score on the trial was the highest score obtained by the participant (. . .) and (b) the score was obtained at most twice by the participant." However, these criteria are arbitrary and do not take into account the total number of items. For example, Duncan et al. (1999) presented their subjects with a minimum of 420 5-letter items. To be an outlier, the maximum score may not appear more frequently than 0.4% (= 2/420). In our studies, the minimum number of 5-elements items was 100 (= 5 exposure durations $*$ min 20 items/condition), yielding to a maximal frequency of 2% to be an outlier. The corollary is a potentially conservative estimate of K in subjects for which we removed trials considered as outliers.

We thus ran new analyses to further investigate the impact of guessing on the parameter estimates, and especially on K. This is of particular relevance for various reasons. It is the first time TVA based investigations are underwent in children, and the first time colour patches are used as stimuli. Children might be more prone to guess, especially in front of less easily discriminable material. We matched the discriminability between letters and colours in young adults. However, children made more errors on colours than on letters during our TVA experiments, suggesting that colours were more difficult to discriminate for their. In these additional analyses, a new parameter was introduced: the guessing rate, p_g. Accordingly, the resulting TVA parameters were corrected for guessing.

TVA estimation of the guessing rate

For each element, the probability of correct report was assumed to result from a two-stage process (Kyllingsbæk & Bundesen, 2007). The first stage is the perceptual identification of the element, which result in VSTM encoding. The probability of VSTM encoding is modelled by TVA equations (see Appendix B and Kyllingsbæk, 2006). If the encoding process fails, a second guessing stage is engaged with probability p_g. At this stage the participant guesses randomly. The following equations (Kyllingsbæk, personal communication) derived the guessing probability, p_g, from a binomial guessing strategy.

Let S_N be the ensemble of all possible stimuli and let S_T be the target set, that is the stimuli randomly drawn from S_N to form a given item. Finally, let R be the set of the stimuli reported by the subject. R is composed of different subsets: R_c: the set of correctly reported targets (defined as the intersection between the stimuli ensemble and the target ensemble $R_c = S_T \cap R$), and R_e the set of targets correctly encoded in visual short-term memory. These sets are related in the following way: $R_e \subseteq R_c \subseteq R$. Let respectively define $P(R_e)$ and $P(R_c)$ as the probability of encoding R_e and reporting R_c. Finally, let $n(S)$ be the cardinal number of S, $\sharp S$, and $\mathrm{Pow}(S)$ the power set of S, that is the set of all possible subsets from S.

In a binomial guessing strategy, there is a constant probability of guessing, p_g, at each of the not encoded targets. Consequently, the probability of reporting exactly the subset reported by the subject, $P(R)$, may be expressed as the product of (i) the probability of encoding a given subset, (ii) the binomial probability of reporting exactly $n(R)$ stimuli, given the encoded subset, and (iii) the probability of actually guessing the exact subset $R - R_e$ that was guessed by the subject, given R_e was reported.

For $n(R) \leq n(S_T)$:

$$P(R) = \sum_{R_e \in \mathrm{Pow}(R_c)} P(R_e) P(n(R) \mid R_e) P(R \mid n(R), R_e)$$

where

$$P(n(R) \mid R_e) = \binom{n(S_T) - n(R_e)}{n(R) - n(R_e)} p_g^{n(R)-n(R_e)} (1 - p_g)^{n(S_T)-n(R)}$$

$$P(R \mid n(R), R_e) = \frac{1}{\binom{n(S_n) - n(R_e)}{n(R) - n(R_e)}}$$

while basic TVA equations were used to model $P(R_e)$ (Kyllingsbæk, 2006). These equations result in 'guessing corrected' TVA parameter estimates.

'Guessing corrected' TVA analyses

For each participant, a model including 11 free parameters was fitted (see Appendix B)[1]: one s, one K, one μ, one t_0, six w-values, and finally one guessing rate parameter, p_g. The best-fitted parameters were estimated by applying a maximum likelihood fitting algorithm to the individual data. As parameters were corrected for guessing all items were used, and no outliers were removed[2].

TVA fits in each of the 15 experimental conditions were fairly close to the colour report raw data. The average Pearson product-moment correlation coefficient was .893 in the control group (*SD*= .16, range: [.85–.94])[3]. Similarly, correlation coefficients indicated sufficiently good TVA fits in dyslexic participants ($r = .89$ and $r = .91$, for LT and YC respectively), very close to the correlations obtained with the 'uncorrected' model.

[1]We simply added a guessing rate parameter, p_g, to the model that minimised the AICc (a bias-corrected AIC for small samples: Hurvich, 1989; Hurvich & Tsai, 1995) and BIC (Schwarz, 1978) criteria in the original analyses (see Appendix B).

[2]A restriction nevertheless came from the 'guessing corrected' equation, which impose that the number of reported stimuli does not exceed the number of displayed stimuli. To fulfil this criterion, a few answers were truncated to the item size by considering only the first $n(S_T)$ reported items.

[3]Correlation coefficients were Fisher z-transformed to compute the means and standard deviations.

Table D.1: *Colours Whole report — 'Guessing corrected' best-fitted TVA parameter estimates*

	K	C	W_{Lat}	p_g
Patients				
LT	3.58 (0.21)	15.33 (1.33)	0.47 (0.03)*	0.29 (.02)
YC	3.55 (0.52)	19.05 (1.89)	0.44 (0.04)**	0.35 (.02)
Control subjects				
CM	3.40 (0.63)	20.01 (2.10)	0.62 (0.03)	0.66 (.02)
CV	5.00 (0.66)	13.93 (1.26)	0.57 (0.03)	0.31 (.02)
TR	3.49 (0.36)	23.12 (2.61)	0.56 (0.03)	0.54 (.02)
AC	4.78 (0.22)	28.14 (2.12)	0.57 (0.03)	0.21 (.02)
LM	3.63 (0.39)	18.45 (1.67)	0.53 (0.03)	0.30 (.02)
PP	3.52 (0.42)	27.96 (2.52)	0.56 (0.03)	0.43 (.02)
TC	4.41 (0.23)	28.04 (2.53)	0.52 (0.03)	0.22 (.02)
Mean	4.03	22.81	0.56	0.38
SD s	0.68	5.60	0.03	0.17

Notes — *K: visual short-term memory storage capacity (number of elements); C: total processing speed (elements.s^{-1}); C_{lat}: laterality index of processing speeds; w_{lat}: laterality index of attentional weights; and p_g: probability of guessing non encoded targets. Standard errors of each estimate are given in parentheses (as estimated by 1,000 bootstrap repetitions).*
$^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$

Parameter estimates were shown in Table D.1, along with the bootstrap *SD*s. Small bootstrap *SD*s, obtained for all parameters but K, further indicate reliable estimates. The only exception is the K parameter, for which particularly large *SD*s were observed. The probability of guessing items that were not encoded in VSTM, p_g, was high, 0.38 on average in the control group (*SD*: .17, range: [.21–.66]). Dyslexic participants' guessing rate did not differ from the control ones. Despite this high guessing rate, 'guessing corrected' TVA parameter estimates were generally in line with the 'uncorrected' analyses. The only exception was observed control subject CV's K estimate. CV's 'guessing uncorrected' VSTM storage capacity was estimated at 3.4 elements, and reached 5.00

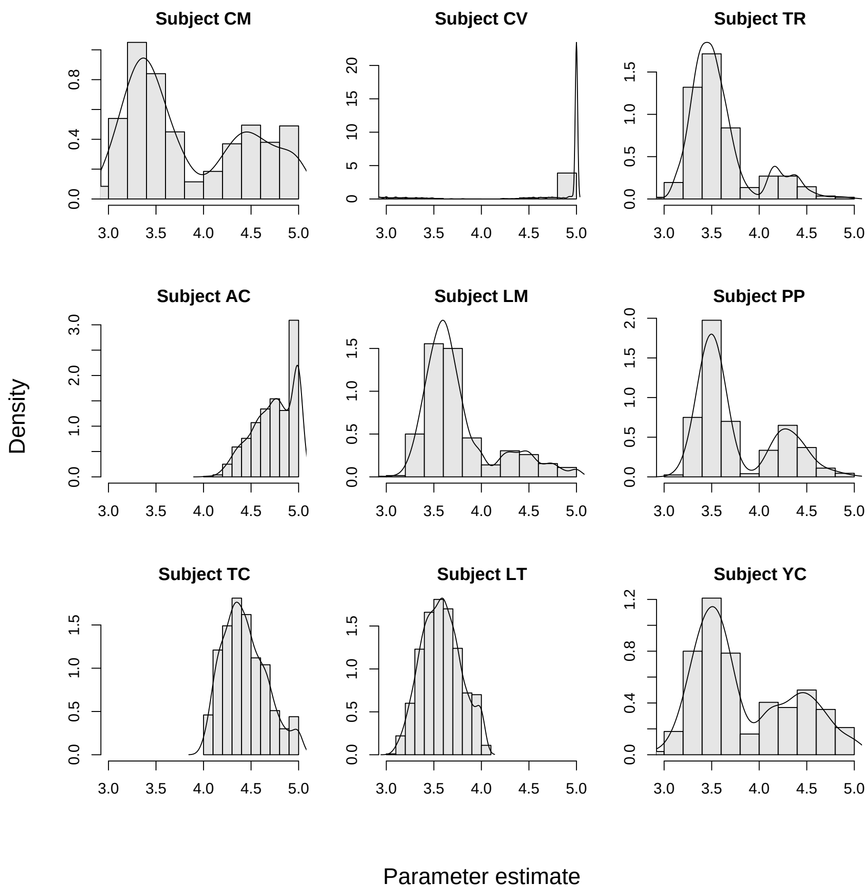

Figure D.1: *Individual bootstrap distributions of the 'guessing corrected' K parameter for colour material. Each panel shows an individual bootstrap probability* density *distribution. It should be noted that most were bivariate, indicating two possible K values: one in the range 3–4, the other in the range 4–5.*

in this 'guessing corrected' analysis. Note that outliers were removed from CV's original data for the first 'uncorrected' TVA analysis, leading to large discrepancies between 'corrected' and 'uncorrected' K estimates. The unreliability of the K estimate was further emphasised by looking at the bootstrap distributions, depicted in Figure D.1. Most distributions were bivariate, suggesting two possible values for K in those subjects. Interestingly, bivariate distributions were only observed for subjects in which outliers were removed. The first peak roughly corresponds to the value obtained when outliers were removed. The presence of a second peak points to the possibility of an underestimation of their VSTM storage capacities. K values obtained for colour material thus heavily rely on the status (outlier vs. not) of a few items for which some subjects achieved their maximal score. Consequently, the 'uncorrected' K values, reported in Chapter 6, must be considered as conservative ones and any theoretical interpretation may be taken with caution.

The same analyses were underwent for the data reported in Chapter 5 and the letter data from Chapter 6. Guessing rates were similar to those observed on colours[4]. Nevertheless, for letters, 'guessing corrected' parameters were in line with the 'uncorrected' ones. More specifically, K estimates were practically identical, and no bimodal distribution was observed[5]. Moreover, the same conclusions stem from 'guessing corrected' and 'uncorrected' analyses. As AICc and BIC values were in favour of 'uncorrected' models, only 'uncorrected' results were reported for letter material.

[4]Guessing rates were compared between letters and colours for control subjects described in Chapter 6, yielding to non-significant results: paired t-test: $t_6 = .207$, $p = .843$.

[5]The only exception was dyslexic participant FA, for which two letter report trials were considered as outliers and removed from the 'uncorrected' analysis. As observed for colour material, the first peak of his bimodal K parameter bootstrap distribution closely corresponded to the 'uncorrected' K estimate, whereas the second peak was located between 4 and 5, also indicating a second possible larger VSTM storage capacity value. Consequently, his VSTM estimate must be considered as conservative.

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