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BEYOND WORDS: A STUDY OF LOCAL VERSUS GLOBAL SHAPE PROCESSING IN DYSLEXIC READERS

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Dissertação orientada pela Doutora Susana Manuela Silva Araújo e coorientada pela Doutora Maria Inês Neto Bramão

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Errata

Errata referente à dissertação de Mestrado intitulada "Beyond words: A study of local versus global shape processing in dyslexic readers", realizada por Diana Sofia Gonçalves Dias.

Na página 31 (Tabela 5) e na página 32 (Figura 7) onde se lê as unidades de tempo, deve ler-se a unidade de tempo dos resultados apresentados em 1/10 milissegundos.

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Abstract

Two processing styles are involved in visual identification of letters/words and objects: either part-based (analytic, local) or holistic (global) processing. Compared with typical readers, dyslexic readers tend to have difficulties implementing local processing to written letters and words. This thesis aimed to explore if these difficulties are restricted to the verbal domain or are more general, affecting the processing of non-linguistic objects. To do so, two experiments were conducted with dyslexic adults and age-matched typical readers to examine object recognition. In Experiment 1, participants performed an object naming task in which we orthogonally manipulated the objects configuration (objects recognized from their global shape vs. objects whose recognition depended on their internal detail) and their visibility (blurred vs. non-blurred images). In Experiment 2, a subset of the same participants performed a difficult object decision task and a superordinate object categorization task (same stimuli) which was assumed to require less object individuation. Relative to controls, dyslexic readers' performance was especially poor (longer RTs) for "internal detail" objects, exacerbated under difficult encoding contexts (blurred images; Experiment 1), and in a task where (presumably) a coarse global shape processing strategy did not suffice for successful object recognition and consequently participants needed to base also on local shape information (i.e., object decision task; Experiment 2). These results seem to suggest that dyslexics process objects in a different manner than controls, and specifically that they could be impaired at part-based processing for object identification. This extends previous findings for written letters/words, hence, are not domain-specific.

Keywords: dyslexia; object processing; local and global shape processing

Resumo

Existem dois estilos de processamento envolvidos na identificação de letras/objetos: baseado em partes (analítico, local) ou holístico (global). Leitores disléxicos (vs. leitores experientes) tendem a ter dificuldades na implementação do processamento local em letras/palavras. Esta tese teve como objetivo explorar se esta dificuldade se restringe ao domínio verbal ou é mais geral, afetando também o processamento de objetos não linguísticos. Duas experiências de reconhecimento de objetos foram realizadas com dois grupos de adultos disléxicos e leitores típicos. Na Experiência 1, os participantes realizaram uma tarefa de nomeação de objetos, na qual a configuração do objeto foi manipulada (reconhecimento baseado na forma global vs. processamento de detalhes internos), assim como a visibilidade (imagens desfocadas vs. não desfocadas). Na Experiência 2, um subconjunto dos participantes realizaram uma tarefa de decisão de objetos e uma tarefa de categorização de objetos (com os mesmos estímulos) que requer menos individuação do objeto. Em relação aos controlos, os leitores disléxicos apresentaram tempos de reação mais longos para objetos de "detalhes internos", exacerbado em contextos de codificação difíceis (imagens desfocadas; Experiência 1), e numa tarefa na qual um processamento global não era suficiente para uma resposta exata sendo necessário que o participante processasse as partes locais (i.e., tarefa de decisão de objetos; Experiência 2). Estes resultados parecem sugerir que os disléxicos processam objetos de forma diferente dos controlos e que podem ser prejudicados no processamento baseado em partes na identificação de objetos. Isto estende evidências anteriores para letras/palavras não sendo, portanto, específicas do domínio.

Resumo Alargado

Existem dois estilos de processamento envolvidos na identificação de letras/palavras e de objetos: processamento baseado em partes (analítico, local) ou holístico (global). O sistema de reconhecimento visual baseado em partes decompõe um objeto ou imagem nos seus constituintes e integra-os de modo a combiná-los com as partes de outros objetos ou imagens, enquanto no sistema de reconhecimento holístico um objeto ou imagem é processado como um todo unificado (Farah, 1992).

Ambos os dois tipos de processamento contribuem para a leitura de palavras, embora o processamento local assuma um papel mais preponderante (e.g., Grainger, 2018; Pelli et al., 2003; Pelli, & Tillman, 2007; Wong et al., 2011; Reicher, 1969; Wheeler, 1970). Um conjunto de estudos tem sugerido que leitores com dislexia de desenvolvimento (perturbação específica da leitura com origem neurobiológica; Peterson & Pennington, 2015) apresentam dificuldades no processamento da estrutura local para reconhecer palavras (i.e., das letras constituintes) e falham na implementação automática do processamento analítico para letras, quando comparados com leitores típicos (Araújo et al., 2014; Fernandes et al., 2014; Lachmann & van Leeuwen, 2008a, 2008b; Zorzi et al., 2012). O presente trabalho pretendeu esclarecer se estes problemas ao nível do processamento local observados na população disléxica não são restritos para letras e palavras visuais, influenciando também o processamento de outras categorias de estímulos visuais tais como objetos. De facto, uma relação entre o reconhecimento visual de objetos e a leitura de palavras é prevista, uma vez que ambos os estímulos são compostos por componentes globais e locais (Farah, 1992; Farah et al., 1998) e partilham processos cognitivos e substratos neuronais durante o seu processamento (McCandliss et al., 2003). A leitura depende de uma rede neuronal especializada, incluindo regiões do córtex ventral occipitotemporal esquerdo (vOT), nomeadamente a área da forma visual da palavra, que fazem parte da via visual ventral

dedicada originalmente ao reconhecimento visual de objetos (Dehaene-Lambertz et al., 2018; Dehaene & Cohen, 2007, 2011; McCandliss et al., 2003). Os estudos de neuroimagem têm também mostrado que os leitores disléxicos têm uma hipoativação do vOT e uma menor laterização à esquerda em comparação com leitores típicos durante a leitura de palavras e também de nomeação de objetos (Martin et al., 2016; McCrory et al., 2005; Richlan et al., 2011). Apesar da possível ligação entre o processamento de palavras e de objetos, a investigação sobre o reconhecimento visual de objetos na dislexia tem sido limitada. Alguns estudos indicam que os disléxicos demoram mais tempo a reconhecer e nomear objetos (e.g., Araújo et al., 2016; Araújo & Faísca, 2019), contudo, não é claro se estas dificuldades podem refletir problemas no processamento local, à semelhança do que já é conhecido e estudado nas palavras (e.g., Araújo et al., 2014).

O objetivo desta tese foi investigar o reconhecimento visual de objetos em leitores disléxicos e, especificamente, a eficiência do processamento local durante o processamento de objetos não linguísticos. Com este propósito, explorámos o desempenho de leitores adultos disléxicos e leitores normativos no reconhecimento visual de objetos, manipulando experimentalmente os objetos e as tarefas usadas no sentido de encorajar a um tipo processamento mais local vs. global. Foram realizadas duas experiências que incluíam três tarefas que envolvem os diferentes estágios do processamento de objetos visuais (sistemas estrutural, semânticos e fonológico; Humphreys et al., 1988; Humphreys et al., 1999). Na Experiência 1, usou-se uma tarefa de nomeação visual de objetos, na qual a configuração do objeto foi manipulada para incluir objetos que podem ser reconhecidos com base na sua forma global (e.g., tesoura ou cadeira) e objetos para os quais o detalhe interno é necessário para a sua identificação (e.g., zebra ou tigre). Manipulou-se ainda a visibilidade dos objetos, que podiam aparecer desfocados ou não-desfocados. O racional foi o de que esta manipulação afeta principalmente o reconhecimento das características internas ou componentes dos objetos (Riddoch & Humphreys, 2004). A Experiência 2 pretendeu confirmar e estender os resultados da Experiência 1, e investigou o processamento de objetos numa subamostra dos mesmos participantes em duas tarefas clássicas de identificação de objetos (construídas com base no estudo com leitores típicos de Gerlach e Poirel (2018)). Usou-se uma tarefa de categorização de objetos, na qual os participantes decidiam se um objeto apresentado correspondia a um objeto natural ou a um artefacto, e uma tarefa de decisão de objetos, onde os participantes decidiam se o objeto apresentado era um objeto real ou um não-objeto (quimérico). Estudos anteriores sugeriram que é necessária uma maior individualização do objeto para decidir se este representa um objeto real ou um não-objeto quimérico do que para categorizar um objeto ao nível superordenado (Gerlach et al., 2000; Gerlach, 2017).

Em ambas as experiências, não se encontraram diferenças significativas entre os dois grupos de leitores em termos de precisão. Estes resultados não são surpreendentes, tendo em conta estudos anteriores e sendo que a amostra foi composta por adultos. Os resultados dos tempos de reação parecem sugerir que os disléxicos apresentam de facto dificuldades no processamento local para objetos. Especificamente, o desempenho dos leitores disléxicos foi particularmente baixo (tempos de reação mais longos) na nomeação de objetos para os quais o reconhecimento depende da atenção ao detalhe interno, e em particular quando a codificação visual foi dificultada através da desfocagem da imagem (Experiência 1), e numa tarefa na qual um processamento global não era suficiente para uma resposta exata sendo necessário que o participante processasse as partes locais e as integrasse (i.e., tarefa de decisão de objetos; Experiência 2).

Os resultados do presente estudo podem ser explicados pelos défices neuronais subjacentes à dislexia. Como já mencionado, os leitores com dislexia (vs. leitores típicos) mostram uma hipoativação em regiões da via visual ventral esquerda, incluindo a área visual da forma das palavras, em resposta a estímulos escritos (Martin et al., 2016; Richlan et al., 2011). Por sua vez, estudos de neuroimagem e estudos com evidência clínica (Yamaguchi et al., 2000; Robertson, & Lamb, 1991) sugerem que a informação local é preferencialmente processada no hemisfério esquerdo, enquanto a informação global é preferencialmente processada no hemisfério direito.

Estas dificuldades no processamento local parecem contrastar com uma vantagem no processamento global típico nos disléxicos (ou, como encontrado em alguns estudos, uma vantagem a este nível). Tem sido argumentado que os disléxicos podem compensar as suas dificuldades e respetiva hipoativação nas regiões do hemisfério esquerdo para letras, desenvolvendo hemisférios direitos "mais fortes" (Stein, 2018, 2019), o que vai no mesmo sentido dos estudos de neuroimagem (i.e., a informação global é preferencialmente processada no hemisfério direito; Yamaguchi et al., 2000; Robertson & Lamb, 1991). Este resultado poderá explicar a vantagem no processamento global em leitores disléxicos, por exemplo, no reconhecimento de figuras geométricas impossíveis (e.g., von Károlyi, 2001; von Károlyi et al., 2003). Por outro lado, outras evidências também sugerem que o processamento holístico de faces (normalmente apoiado pelo giro fusiforme direito; Dehaene & Cohen, 2011; Farah et al., 1998) está intacto em leitores disléxicos (Sigurdardottir et al., 2015, 2019).

Outra possibilidade é a de que os resultados do presente estudo não se explicam por problemas no processamento percetivo (processamento baseado em partes) mas antes por dificuldades nos disléxicos ao nível atencional, relacionadas com um desenvolvimento atípico do sistema magnocelular na via dorsal do córtex visual (Stein, 2001, 2018, 2019), ou por dificuldades na alternância entre estratégias de processamento (i.e., *switching cost*; e.g., Hari & Renvall, 2001). No entanto, estas explicações parecem improváveis ou não são respondidas devido ao desenho experimental do presente estudo.

A reduzida amostra utilizada (sobretudo na Experiência 2) e, consequentemente, as análises adotando um pressuposto de homogeneidade do grupo de leitores disléxicos são limitações deste estudo. No entanto, o presente estudo encontrou novas evidências que podem ter implicações para a prática clínica, pois a deteção de dificuldades no reconhecimento visual de objetos pode ser usada como um dos indicadores quando se pretende asseverar um diagnóstico de dislexia.

Em suma, no presente estudo encontrámos novas evidências sugerindo que as dificuldades no processamento baseado em partes por leitores disléxicos não são específicas de um domínio, mas sim que se estendem a outras categorias, tal como objetos. O processamento global, por sua vez, parece estar intacto na dislexia. Nenhum outro estudo que tenhamos conhecimento explorou o processamento local e global na população disléxica usando tarefas que exploram todos os estágios relacionados ao reconhecimento de objetos, no entanto, será importante investigações complementares para explorar estes resultados.

Palavras-chave: dislexia; processamento de objetos; processamento local e global

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Introduction

It has been proposed that the cognitive processes engaged when reading a word overlap to a large extent with those when recognizing and naming a familiar object (Price et al., 2006; Wolf, 1991). In both instances, we perceive and identify a visual stimulus and retrieve its associated lexical form, which is then output during articulation. There is also ample evidence showing that naming performance is an important correlate and longitudinal predictor of reading ability, and it also distinguishes between typical and impaired readers because the latter group tends to perform less accurately and more slowly (e.g., Araújo & Faísca, 2019; Araújo, Reis et al., 2015; Wolf & Goodglass, 1986).

Individuals with developmental dyslexia (henceforth, dyslexia), which is a persistent reading disorder despite adequate intelligence and no general learning problem (Peterson & Pennington, 2015), have severe difficulties in acquiring basic reading subskills such as word identification, phonological awareness and decoding (Vellutino et al., 2004; for a recent meta-analysis, see Carioti et al., 2021), and also at recognizing and naming visual items including of every-day objects (for a meta-analysis on confrontation and serial naming tasks, see Araújo & Faísca, 2019). At behavioral level, children and adults with dyslexia (including "high-functioning", university students) perform worse than age-matched controls in tasks where individual or a series of familiar objects are to be named as quickly as possible (e.g., Jones et al., 2009; Kirby et al., 2003; Landerl & Wimmer, 2008). It is not clear why this is the case. Using high-temporal resolution event-related potentials (ERPs), Mayseless and Breznitz (2011) and Araújo and colleagues (2016) suggested that differences in processing objects between dyslexic and typical readers appear from the early stage of visual processing. For example, Araújo et al. (2016) observed a facilitatory visual priming effect during object naming (e.g., a picture of a NAIL primed by a picture of a PENCIL) as early as the N/P190 and N300 ERP components, signaling early and late visual processing respectively, but only in typical readers, not in dyslexic readers. This result suggests that a suboptimal visual processing of objects might contribute to the naming deficits that characterizes dyslexia. The extent to which the perceptual strategies used by readers with and without dyslexia for the recognition of visual objects differ remains almost unexplored and was the focus of the present work.

Two processing styles are assumed to be involved in visual recognition of objects: either part-based or holistic processing. In a comprehensive review of visual object recognition, Farah (1992) proposes that a part- or feature-based recognition system decomposes an object or image into its constituents and integrates them in order to match them with the parts of other objects or images, whereas in the holistic recognition system an object or image is processed as a unified whole or “Gestalt”. Neuroimaging studies on visual object recognition have supported the idea that objects comprise “local” information sampled from relatively small regions of the sensory input (e.g., edge and boundaries, and local part structure) and “global” information sampled from larger regions (e.g., overall spatial configuration, symmetry, and orientation), that are processed at different time courses during object perception (we return to this issue latter on; Leek et al., 2016). It is worth mentioning, however, that there are multiple definitions of parts-based (local, analytic) and holistic (global) processing, and this division takes a different dimension when it comes to printed words and objects (Farah, 1992). Processing printed words requires that a reader computes the identity of the individual constituents (i.e., letters) alongside with their relative positions in the word (i.e., a process referred to as orthographic processing), in order to be able to access the word sound and meaning (Grainger et al., 2012; Grainger, 2018). In turn, in object recognition, some form of structural description has been hypothesized (e.g., Biederman, 1987; Marr, & Nishihara, 1978). It has been proposed that an object’s (global) shape is represented in terms of different parts, and these parts are explicitly represented as shapes in their own right, along with independent relations among each other. Therefore, both part-based (local) and holistic (global) processing are needed for object recognition (Farah, 1992).

A small body of research has investigated non-word visual object and face recognition abilities in dyslexia (e.g., Araújo et al., 2016; Sigurdardottir et al, 2015), and these studies in turn did not distinguish between local and global visual processing during object recognition. Before discussing these studies and present the rational of our work, a starting point is to go over characteristics of visual letter and word processing, which constitutes a hallmark deficit in dyslexia, and the link between word and object processing.

Visual Letter and Word Recognition

Reading might depend more on local (by-parts or, as often referred, analytic) processing of the individual components of words, albeit holistic processing also contributes to expert word reading, as reflected at behavioral and brain levels (e.g., Beaucousin et al., 2013; Grainger, 2018; Pelli et al., 2003; Pelli & Tillman, 2007; Proverbio et al., 1998; Yamaguchi et al., 2000; Wong et al., 2011). Indeed, Pelli and Tillman (2007) observed that when proficient adult readers are asked to read a text using a rapid serial visual presentation of words, substitution by similar letters on the original text, and consequently a disruption of letter-based processes while preserving the word shape, is extremely devastating for reading rate. They also found that letter-decoding accounts for about 62% of the adult reading rate, while holistic word recognition together with sentence context account for 38% of the reading rate. Of note, recent studies suggested that the extent to which a reader processes words in a more local manner depends on the specific language and orthography (e.g., Ben-Yehudah et al., 2019).

Evidence for a processing by-parts during word recognition comes also, for example, from the literature of the transposed-letter effect. Perea and Lupker (2003, 2004) used a masked priming paradigm combined with a lexical decision task (where participants had to decide if a letter string was a real word or not), in which the prime and the target word could differ either by transposing two adjacent letters (e.g., u**hs**er – U**SH**ER) and nonadjacent letters (e.g., ca**n**i**s**o – CA**S**I**N**O) or replacing the letters (e.g., u**fn**er - U**SH**ER or ca**v**i**r**o - CA**SIN**O) in a word. The authors showed that transposing letters in a word activates to a greater degree (i.e., led to faster responses) the representation of the target word compared to replacing letters. These results suggest that there has to be a previous step before the recognition of the whole word, in which the individual parts (letters) of the word are recognized. Their position in the word is probably flexibly coded, otherwise "caniso" and "caviro" would equally facilitate the activation of the representation of CASINO.

The observation of crowding effects (i.e., the interference from neighboring stimuli on target recognition) has also been interpreted as an indicator of recognition by parts in readers. In a study with typical adult readers, Martelli et al. (2005; Experiment 2) manipulated the space between letters in a word horizontally. The authors found that visual word recognition is possible, but only when the letters are spaced far enough apart from each other, which suggests that the reading system needs to isolate the parts and recognize each individual letter to then be able to process the whole word. In the same line is the well-known length effect, showing that the number of letters in a word affects visual word recognition and reading (i.e. faster reading of shorter words; Barton et al., 2014). Pelli et al. (2003) examined letter and word recognition efficiency when presented in background noise and found that recognition efficiency was inversely proportional to word length (i.e., the greater the word length the less efficient word recognition was, as there was a drop in efficiency for longer words), and that accuracy never exceeded that predicted by letter- or feature-based models. The results again indicated that the visual system detects small components (letters or features of letters) and then recognizes the whole specified by these components.

Interesting, a number of studies suggested that literacy acquisition and experience per se shape the visual system, and specifically, enhances local processing of linguistic and also non-linguistic stimuli. For example, Malik-Moraleda and colleagues (2018) asked literate and illiterate adults to perform a character search task where they had to decide whether a given character had been previously presented within a string, which could be made of letters forming (pseudo)words or of pictograms (non-linguistic string). Overall, literate participants showed a better performance than illiterate participants in accessing the individual characters of linguistic and nonlinguistic strings, being this difference higher for the former stimuli. This result suggests that reading acquisition improves the ability to identify constituents in (non)linguistic strings, in other words, a parts-based mode of visual processing. Ventura et al. (2013) extended these results by showing that literacy affects the ability to deploy a more local and flexible processing of faces and houses.

It is, however, worth noting that both part-based and holistic processes are not mutually exclusive, as the orthographic system is rather flexible and may lie in between both depending on the context. In fact , a global processing for linguistic stimuli (i.e., recognition of words as a whole) is also engaged by expert word recognition, as endorsed for example by the classic word superiority effect. This effect corresponds to a better performance in recognizing a letter when presented within a word context than when presented in isolation or in a nonword/scrambled word context (Reicher, 1969; Wheeler, 1970). The observation of this effect has been interpreted as suggesting that word (or letter-cluster) representations are also activated during word processing and influence the activation states of lower levels (i.e., of individual letter representations). Wong and colleagues (2011), using a composite matching paradigm (widely used for faces), also found evidence of expertise-related holistic processing of words. Two words appeared sequentially and participants were cued to judge if the target parts (either the left or right halves) of the two words were identical or not while ignoring the non-cued irrelevant part. The two words presented could be either congruent (both halves matched or mismatched) or incongruent (one half matched and the other half mismatched) and the two halves could be vertically misaligned or aligned (interference may be reduced when the configuration of parts is disrupted). The results showed interference from the irrelevant part, as responses were faster for the congruent (vs. incongruent) condition, and such congruence effect was larger when the parts were aligned versus misaligned; this pattern is characteristic of holistic face processing. These results indicate the obligatory attention of all parts despite the instruction to focus only on the target part. This type of word processing uses the orthographic knowledge stored in memory (such as memory for letter patterns and words), acquired through reading experience and print exposure (Apel, 2011; Kirby et al., 2008).

Important for the present work, the literature has demonstrated that anomalous letter processing and slow and/or inaccurate word decoding are a hallmark of dyslexia (reflected in behavioral and neural markers, e.g., Araújo et al., 2012; Araújo, Faísca et al., 2015; De Luca et al., 2010), and some studies suggested that the perceptual strategies used by dyslexic and typical readers in letter and word recognition may not be the same. Specifically, readers with dyslexia tend to show more difficulties in processing local part structure while recognizing a word and fail to automatically implement analytic processing to letters to the same extent as skilled readers (e.g., Araújo et al., 2014; Fernandes et al., 2014; Lachmann & van Leeuwen, 2008a, 2008b; Zorzi et al., 2012). For example, using a visual lexical decision task, Araújo and colleagues (2014) observed that, as expected, words were responded faster than pseudowords (lexicality effect), but a greater difference was found for the dyslexic children (vs. age-matched controls), for whom pseudowords were especially hard. As for pseudowords there is no lexical representation stored in the orthographic lexicon (as expected for familiar words), and thus, processing is based on a sequential decoding procedure, the so-called sublexical reading route in reading models such as the dual route cascaded model (Castles et al., 2006; Coltheart et al., 2001). The sublexical route is thought to be related with a part-based processing of words, as it congregates the letters into phonology serially, letter by letter. Thus, the observed stronger lexicality effect by dyslexic readers suggests more effortful letter-by-letter reading in these readers compared to controls. Also, in Araújo et al. (2014), short items were responded faster and more accurately than long ones, and this length effect affected more the dyslexic group for both words and pseudowords. The performance of typical readers was only affected by the length of pseudowords. This result suggests that unlike controls, dyslexic readers may predominantly use the sublexical route regardless of the item being a word or a pseudoword, albeit inefficiently, which would explain the fact that these children are slower in both type of items.

The Congruence Effect (CE) highlights the involvement of local or more global processing in letter identification. Given that early visual processes combine features of an object with those of its surroundings (i.e., the occurrence of visual feature binding), it should be easier to recognize a visual object when it is surrounded by a similar shape than when it is surrounded by a dissimilar one, reflected by the CE (Lachmann & Van Leeuwen, 2008a, 2008b). When adult readers are asked to compare two items surrounded by a congruent or an incongruent shape that they should ignore, there’s a CE for pseudo-letters but not for letters (Lachmann & Van Leeuwen, 2008a). These results are interpreted as assuming a local/analytic processing for letters (i.e., the letter is not grouped with its irrelevant surrounding information) and a global processing for pseudo-letters (i.e., the pseudo-letter shape is grouped with its surrounding). However, this dissociation is not observed in readers with dyslexia. Using a sequential same-different matching task, Fernandes and colleagues (2014) and Lachmann and Van Leeuwen (2008b; for the subtype "frequent word reading impaired") observed that dyslexic children also showed a CE for letters. These results seem to suggest that dyslexic readers failed to apply the analytic processing strategy, in terms of suppressing irrelevant surrounding information for letters.

Another line of evidence that seems to signal dyslexics' difficulties in implementing the local processing to letters/words comes from work on crowding. In a study by Zorzi and colleagues (2012), children with and without dyslexia had to read short sentences in normal or spaced (i.e., interletter and interline spacing and space between words were increased) conditions, and in a study by Bertoni and colleagues (2019; experiment 2), sentences were presented in extra-small or extra-large spaced conditions. The results of both experiments showed that increasing the space between the letters improved text reading accuracy and speed, especially in dyslexic readers. The manipulation of spacing can influence letter identification by reducing crowding effects, which in turn facilitates local (letter component) processing. This seems to be especially helpful for dyslexic readers.

In sum, so far, we presented evidence that the orthographic system uses both a part-based and a holistic processing of letters and words (e.g., Pelli et al., 2003; Wong et al., 2011), albeit the former is thought to be especially important for visual word recognition (e.g., Pelli &Tillman, 2007). However, some evidence suggested that dyslexic readers have a suboptimal local processing of written letters/words (e.g., Araújo et al., 2014; Fernandes et al., 2014; Lachmann & van Leeuwen, 2008b). This thesis aimed to explore if these difficulties extend beyond the verbal domain, influencing visual object processing.

Beyond Words: Visual Object Recognition in Readers with Dyslexia

A relation between visual object recognition and reading is predicted because both involve similar cognitive processes and encoding of multiple parts (local components) is critical for objects and words (Farah, 1992; Farah et al., 1998).

Word and visual object recognition also share neural underpinnings (e.g., McCandliss et al., 2003). Reading relies on a highly specialized neural network including regions of the left ventral occipitotemporal (vOT) cortex, namely the Visual Word Form Area (VWFA), which is highly reproducible across subjects from different writing systems and scripts (e.g., Feng et al., 2020; Nakamura et al., 2012). The VWFA is especially responsive to visual words and letters compared to nonletter symbols and lesions in this region cause selective deficits in word recognition (Dehaene & Cohen, 2011; McCandliss et al., 2003). However, the human brain cannot have evolved a dedicated mechanism for reading, as this skill is a recent cultural acquisition (with about 5000 years) for which there was not enough time to have influenced the human genome (Dehaene & Cohen, 2007, 2011). Dehaene and Cohen (2007) proposed the neuronal recycling hypothesis, which proposes that reading "invaded" or adapted evolutionarily older brain circuits that are sufficiently close and plastic enough to allow that part of their neurocognitive resources are reallocated to the new function of reading. In fact, it seems that the left occipitotemporal region that supports reading is part of the ventral visual stream that evolved originally for visual object recognition (Dehaene-Lambertz et al., 2018; McCandliss et al., 2003). A recent study with healthy children by Dehaene-Lambertz and colleagues (2018) found that prior to schooling the VWFA could not be detected but after only 2/4 months of literacy instruction this region emerged at its adult location. Interesting, the emergence of this area does not seem to alter the organization of the ventral visual response to other objects (i.e., faces, houses, bodies, or tools). In fact, the VWFA interposed on more lateral sectors of the cortex, within the left occipitotemporal sulcus, that is weakly specialized for the other objects. This study suggests that the neurocircuits are plastic enough to allow the emergence of the VWFA, as this region seems to emerge at a fixed and weakly specialized location without altering the preexisting responsivity to other stimuli.

Important for this work, neuroimaging studies revealed that dyslexic readers have a dysfunction in the vOT cortex, with hypoactivation in the left fusiform gyrus (including the

VWFA) in response to letters and a less left laterization compared with typical readers (for meta-analysis, see Martin et al., 2016 and Richlan et al., 2011). Brem and colleagues (2020) recently found that print-sensitive activation in the VWFA was positively associated with reading fluency by dyslexic children (i.e., the slower their reading, the lower print-sensitive activation in this region), suggesting a link between activation in this region and the severity of reading difficulties in dyslexia. Yet, abnormal (reduced) activation in the vOT is not specific to orthographic decoding, as it was observed during both word reading and object naming by dyslexic readers (McCrory et al., 2005), suggesting a common neural basis for both deficits.

As mentioned, behavioral studies showed that children and adults with dyslexia are usually slower (and sometimes less accurate) than typical readers at recognizing and naming objects (e.g., Araújo et al., 2019; Araújo et al., 2020; Fawcett & Nicolson, 1994; Nation, 2005; Sigurdardottir et al, 2015; Snowling et al., 1988), which also manifests in atypical brain responses (e.g., Araújo et al., 2016; Mayseless & Breznitz, 2011), in addition to their difficulties with reading. For example, Fawcett and Nicolson (1994) found that children with dyslexia were significantly slower at naming objects compared to chronological-age controls, and importantly, even when compared to reading-age controls; hence, it is unlikely that the delay is merely caused by dyslexics' poor reading level. These difficulties are persistent, as even adults with dyslexia commit more errors in naming objects (with a discrete naming task: e.g., Araújo et al., 2016) and exhibit longer object naming times (with a RAN task: e.g., Araújo et al., 2020). Furthermore, other studies reported difficulties by dyslexic readers on visual recognition tasks that require the individuation of exemplars within a category of objects such as birds, cars or houses (Sigurdardottir et al., 2015). It is not clear, however, why this is the case. It might be that processing differences underlie such problem, which remains largely unexplored.

Indeed, according to influential cognitive models of object recognition, we recognize objects through a hierarchical process that includes a part-based stage, in which the components of an object are decomposed, and then a stage in which we extract the configural structure that binds them together (e.g., Biederman, 1987; Marr & Nishihara, 1978). There is evidence (e.g., Gerlach & Poirel, 2018; Riddoch & Humphreys, 2004) suggesting that depending on the context it might be beneficial to use a global processing in object recognition, that is, whenever the global shape of an object is sufficient to its correct identification (e.g., the outline shape of a scissor or a chair is easy to distinguish and is informative about the identity of the object), but sometimes the individual, local parts composing the object need to be identified separately for a correct object identification (e.g., if the individual parts are functional components or diagnostic features, such as the stripes in a tiger or a zebra).

The availability of different processing styles during object processing is supported by neuropsychological and electrophysiological data. For example, Riddoch and Humphreys (2004; Experiment 2) found that two simultanagnosic patients (who suffered from deficits in identifying multiple stimuli and in interpreting complex scenes) were more accurate at naming those objects that could be named from their outline (global) shape (e.g., a picture of a bear) than those in which the internal detail (parts) was needed for identification (e.g., a picture of a cabinet), unlike controls who performed at or near ceiling with both stimuli. Studies with electroencephalography (EEG) in turn have contributed to describe the temporal course of object perception. For example, Leek and colleagues (2016) and Oliver (2017), using three dimensional and complex possible and impossible objects respectively, described an initial and rapid extraction of global shape information (around 150ms post-stimulus onset; N1 component) and a later extraction of local shape structure (around 250ms post-stimulus onset; N2 component) during object processing.

Only a few studies attempted to shed some light on the mechanisms underpinning the visual object recognition and object naming difficulties that characterizes the dyslexic population, and specifically whether these relate to differences in processing. A surprising result was found by von Károlyi (2001) and von Károlyi et al. (2003) in a visual-spatial task in which adolescents with and without dyslexia had to indicate if a 3D figure represented a possible or an impossible figure. The rationale behind this task was that scanning an impossible figure part by part yields the misperception that the figure is possible, and only by integrating the parts in a whole one can recognize that these parts conflict and that the figure is actually impossible. Therefore, to be able to perform the task successfully, a figure must be processed holistically. The results of both studies revealed that dyslexics were significantly faster than the controls at recognizing impossible figures (with no statistically significant cost in accuracy), which could suggest superior holistic processing of objects in dyslexic readers. Diehl and colleagues (2014) replicated these two studies, by reporting faster latencies for the impossible figures as reading skill decreased (i.e., participants who were worse at reading displayed a speed advantage). Taken together, these studies suggest that dyslexia might be associated with an enhanced ability to process visual-spatial information globally.

The literature on face processing seems also to suggest intact holistic processing in dyslexia. Sigurdardottir et al. (2015) measured the degree to which dyslexic people use holistic face processing. Three composite faces (i.e., upper half of one individual face combined with the lower half of other face) were shown and the participants were asked to indicate which face contained the same target part as a study face. Although dyslexic readers showed poor overall performance, they lack of a significantly smaller or greater congruency effect compared to the controls demonstrated that their holistic face processing is no different from that of typical readers. Likewise, Sigurdardottir et al. (2019), using a feature-based and a global form face matching task, found that dyslexic readers were worse at feature- or part-based processing of faces compared to typical readers, while no group differences were found in global processing of faces. These results suggest that word and face perception are associated when the latter requires the processing of visual features (which is weakened) and that reading problems are independent of the processing of global form. So, this study shows that dyslexic readers could have difficulties in local processing.

In sum, object (and face) recognition problems are still found in dyslexic readers albeit their holistic processing appears to be intact, suggesting that dyslexics may instead be specifically impaired at part-based processing of visual objects. However, this hypothesis awaits further experimental testing.

The Present Study

Holistic (whole-based) and local (part-based) object processing have been identified as separable approaches to visual object recognition (Farah, 1992), and it is possible that their efficiency differs in individuals with and without dyslexia, much like in processing visual letters and words (e.g., Araújo et al., 2014; Fernandes et al., 2014). If the hypothesized local processing difficulties are a hallmark of dyslexia, then these should extend beyond visual letters/words and generalize to the processing of other categories such as objects. Hence, the aim of this thesis was to investigate visual object recognition ability in dyslexic readers, and specifically, whether these readers are disadvantaged at using a part-based processing of objects. To do so, we explored dyslexic and control adults' performance in visual object recognition, where the visual objects and task demands were experimentally manipulated in order to tap into a specific (local vs. global) processing.

Two experiments were conducted based on the stages of information processing involved in visual object recognition (Humphreys et al., 1988; Humphreys et al., 1999). Theories of object recognition hold that knowledge about the shape of the object is first accessed (i.e., structural descriptions), which allow us to identify the visual percept as a familiar object. Second, knowledge about the functional and associative properties (i.e., semantic representations) is accessed. Finally, knowledge about the phonological description of the object is activated (i.e., name representations), which allow us to name the object. Three tasks that may cause access to the structural, semantic and the phonological systems were constructed, as potential difficulties in the local processing by dyslexic readers may be evident in tasks that involve these different systems.

In Experiment 1, we used a visual naming task of everyday objects, modeled by Riddoch and Humphreys (2004; Experiment 2). This task taps into the “name representations” stage of visual object processing (Humphreys et al., 1988; Humphreys et al., 1999), as the participants had to name aloud the objects. Based on prior neuropsychological studies (e.g., Riddoch & Humphreys, 2004), we orthogonally manipulated the object configuration by including objects that could be recognized from their global shape and objects whose recognition depended on their internal detail in two visibility conditions (blurred and non-blurred). We predicted that if dyslexic readers are specifically impaired at part-based processing of objects, then, relative to controls, they should show greater difficulties at recognizing “internal detail” objects. Such difficulties should be exacerbated in the blurring condition, given that image blurring impairs the recognition of internal details of objects and parts more than the global shape.

Experiment 2 aimed to extend the results from Experiment 1 and investigated object recognition by using two other standard tasks: superordinate object categorization and object decision, modeled by Gerlach and Poirel (2018). The object categorization task taps into the “semantic representations” stage (Humphreys et al., 1988; Humphreys et al., 1999), as the participants have to access the object category and knowledge about its functional properties (e.g., fruit, animal), while it was assumed that the object decision task taps into the “structural descriptions” stage (Humphreys et al., 1988; Humphreys et al., 1999), as the participants identify the image as a familiar object and have to access knowledge about its form. In order to decide whether an object is a natural object or an artifact (i.e., categorization task), it may be sufficient to recognize its global shape, and thus, this task is thought to require less object individuation than deciding whether an object presented exists or not (i.e., object decision task). Because we used chimeric non-objects in the object decision task, a more detailed shape processing is needed as these non-objects may have similar global shapes as real objects and indeed contain parts of real objects (Gerlach & Poirel, 2018). Therefore, our prediction was that dyslexic readers' performance would be more impaired in the object decision task than in the object categorization task (with the exact same objects) compared to the typical readers. This result in turn would converge with Experiment 1.

Experiment 1

Methods

Participants. From an initial group of 73 adults with behavioral data collected, 10 were excluded due to low behavioral performance (n = 7; accuracy was ≥ 3*SD*s lower than the group mean), because did not meet the dyslexia criteria (n = 2; word reading scores were in the normal range; see below for details) and due to low nonverbal IQ (n = 1). The final sample consisted of 27 adults with developmental dyslexia (17 females) and 36 typical readers (26 females), matched on years of education, age, and nonverbal IQ (*t*-tests, all *ps* > 0.3; see Table 1). All were native Portuguese speakers, with normal or corrected-to-normal vision and no known history of neurological diseases or psychiatric disorders (self-reported). The participants were recruited from an existing pool (Araújo et al., 2016) and throughout advertisement via social media (e.g., Facebook groups) and the Gabinete de Apoio Psicopedagógico ao Estudante (GAPE) at Faculdade de Psicologia of Universidade de Lisboa.

All dyslexic participants had received a formal dyslexia diagnosis by a specialized therapist during their childhood/adolescence, and still consider their reading level inadequate. In addition, they all scored below the 5th percentile of the age norms of the 3DM reading fluency test (timed reading of single words and pseudowords; Pacheco et al., 2014) and on sentence reading and comprehension (1-min TIL test, adapted for college students: Fernandes et al., 2017). Control participants had no history of reading and/or spelling problems and showed word reading scores in the normal range (> 25th percentile in both tests). All participants from both groups had normal range nonverbal IQ (≥ 7 standardized score on the Matrix Reasoning subtest from the Wechsler Adult Intelligence Scale – WAIS-III; Wechsler, 1996). The demographic variables and mean performance of both groups of readers on cognitive and literacy measures can be seen in Table 1.

Participants gave informed written consent and were compensated (with Vouchers Pingo Doce) for their participation in the study.

Table 1

Demographic Variables and Average Performance on Cognitive and Literacy Tests of Dyslexic and Typical Readers, and Group Differences (t-test)

Variables	Dyslexic Readers (N = 27)	Typical Readers (N = 36)	*t-value*
Age	23.00 (3.12)	23.42 (4.87)	-0.39
Years of Education	14.07 (2.11)	13.81 (2.01)	0.51
Matrix Reasoning	11.44 (2.53)	11.97 (2.16)	-0.89
3DM (Items/Sec)	1.14 (0.25)	1.89 (0.22)	-12.76*
1-Min TIL (Max.= 36)	9.56 (2.33)	16.14 (2.65)	-10.27*

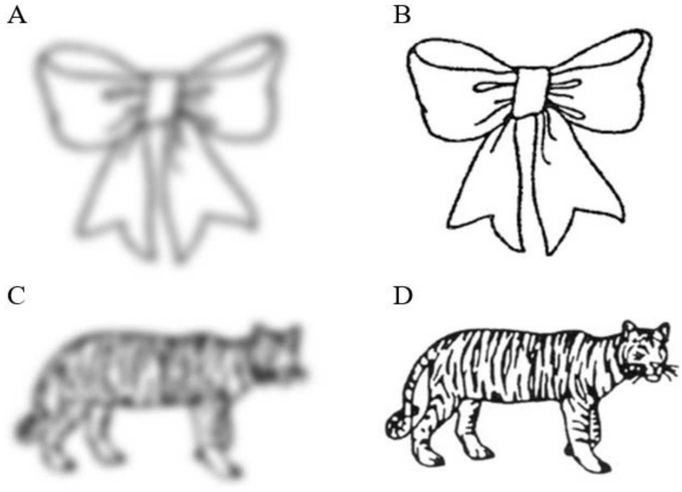
Note. *SDs* are presented in parentheses. $*p < 0.001$

Materials. A total of 200 black and white line drawings of everyday objects were selected from the set of Snodgrass and Vanderwart (1980). These objects were selected in order to encourage either the use of global or local processing during object recognition, inspired by prior work with neuropsychological patients (e.g., Riddoch & Humphreys, 2004). To do so, object configuration was manipulated by including objects that could be recognized from their global shape alone ("global shape" objects) and objects that required attention to internal detail and constituent parts/features to be identified ("internal detail" objects). Assignment of the stimuli into these two experimental categories was based on whether the objects could (or could not) be correctly identified when presented as silhouettes (i.e., after removing all interior features), following prior work by Wagemans et al. (2008). These authors modified a large pool of object line drawings into silhouettes and asked participants to name these objects. The rationale is that if the participants' naming accuracy is high in the silhouette version of an object (e.g., the object CHAIR obtained 95% correct responses in the silhouette version), then this indicates that this object can be recognized from its global shape alone. On the other hand, if the naming performance is very low when the object is presented as silhouette, this indicates that successful recognition of that object is dependent on information about its internal detail (e.g., internal features such as surface markings are crucial for recognizing a ZEBRA, and thus after removing this information its recognition falls down to ~ 1%). Thus, in the present study, based on the identification norms by Wagemans et al. (2008), 100 objects were selected for the "global shape" condition (GS), for which the performance on their silhouette version was above 80%, and 100 objects were selected for the "internal detail" condition (ID), for which the accuracy performance was below 50% on their silhouette version. Additionally, the visibility of these objects was manipulated, by creating a blurred (BL) and non-blurred (NB) version for each object. Blurring increases the difficulty of visual encoding, by removing the surface details of an object image, and is assumed to affect more the recognition of objects where the internal detail is needed for identification (Riddoch & Humphreys, 2004). This orthogonal manipulation of object configuration by visibility resulted in four experimental conditions comprising 50 items each (GS/BL, GS/NB, ID/BL, ID/NB; see Figure 1 for an example), which were matched for frequency of the objects' name (Corlex frequency database: Bacelar do Nascimento et al., 2007), age of acquisition, familiarity and visual ambiguity (Portuguese norms for the Snodgrass and Vanderwart's set: Ventura, 2003), pictures' visual complexity (Szekely & Bates, 2000) and category (living, non-living) (*t*-tests, all *p*s > 0.2, except for visual ambiguity: $p = .132$).

There were two pseudorandomized stimulus lists: in list 1 an object appeared in the blurred condition and in list 2 that same object appeared in the non-blurred condition. The lists were balanced among the participants in each group, so that each participant only saw one list during the experiment.

Figure 1

Example Display of One Trial of the Object Naming Task, for Each Condition



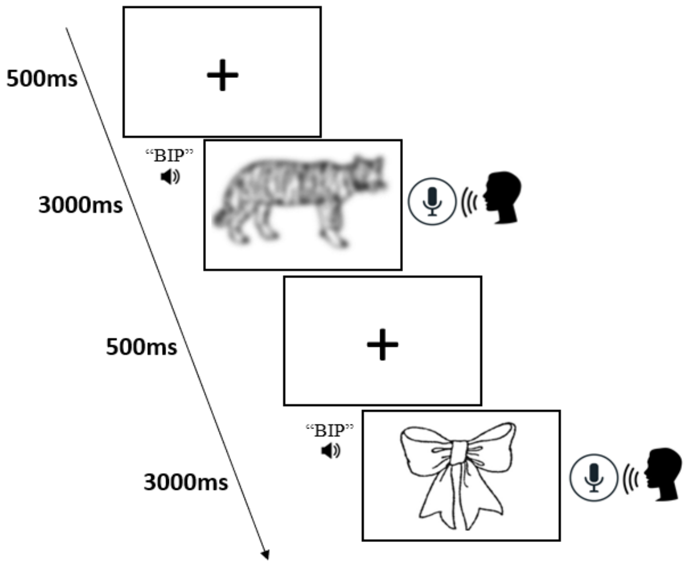
Note. A. Global Shape/Blurred Condition; B. Global Shape/Non-Blurred Condition; C. Internal Detail/Blurred Condition; D. Internal Detail/Non-Blurred Condition.

Experimental Procedure. Participants were seated in front of a computer screen and were instructed that they would be shown line drawings of familiar objects that could be blurred or not and that they should try to name aloud these objects as quickly and accurately as possible. The sequence of events was as follow (Figure 2): a fixation cross "+" appeared at the center of the screen for 500 ms, followed by the presentation of a sound "bip" (signaling the beginning of each object presentation) and of the picture of the object for 3000 ms, which the participants should name out loud. All pictures (500 x 362 pixels) were presented centrally on a white background on a computer screen and subtended about 5º (height) by 7º (width) of visual angle. Before the task, participants performed 10 practice trials in order to be adequately familiarized with the experimental task.

Stimulus presentation and behavioral data collection were controlled by Presentation software (version 22.1; https://www.neurobs.com/). Accuracy and reaction times were recorded.

Figure 2

Sequence of Events in the Object Naming Task



Results

Mean percentage of accuracy and mean reaction times (RTs) for correct responses were calculated. A distribution-based criterion was used to reduce the impact of possible outliers, i.e., RTs greater than 3 SD beyond the subject and condition means were discarded (~2.5% of the data). The significant differences for the different stimulus conditions and for each group were tested with repeated measures ANOVAs, including object configuration (global shape vs. internal detail) and visibility (blurred vs. non-blurred) as within-subject factors and group as a between-subject factor (dyslexic readers vs. typical readers). Post-hoc analyses (Tukey HSD test) were conducted to investigate significant interactions.

Accuracy. Both groups of readers performed with comparable levels of accuracy ($F(1,61) = 1.93$, $p = 0.17$, $\eta^2 = 0.03$). Participants showed high accuracy in performing the task with both the "global shape" (dyslexics: $M = 95.86$; $SE = 0.60$; typical readers: $M = 97.29$; $SE = 0.52$) and the "internal detail" (dyslexics: $M = 87.66$; $SE = 0.86$; typical readers: $M = 88.32$; $SE = 0.75$) objects, as well as with both non-blurred (dyslexics: $M = 93.97$; $SE = 0.64$; typical readers: $M = 95.11$; $SE = 0.55$) and blurred (dyslexics: $M = 89.56$; $SE = 0.78$; typical readers: $M = 90.50$; $SE = 0.67$) images.

The main effects of object configuration ($F(1,61) = 186.83$, $p < 0.001$, $\eta^2 = 0.75$) and visibility ($F(1,61) = 64.01$, $p < 0.001$, $\eta^2 = 0.51$) were significant, because "global shape" objects were identified more accurately than "internal detail" objects, and participants also showed a better identification when the objects were non-blurred than blurred. A significant two-way interaction between object configuration and visibility ($F(1,61) = 25.15$, $p < 0.001$, $\eta^2 = 0.29$) further indicated that blurring specifically affected the "internal detail" objects, which were harder to identify when presented as blurred than non-burred, while participants were as accurate in blurred and non-blurred versions of the "global shape" objects.

Finally, the two-way interactions between group and object configuration and between group and object visibility were not statistically significant (both *Fs* < 1), neither was the triple interaction group x object configuration x object visibility ($F(1,61) = 2.74$, $p = 0.10$, $\eta^2 = 0.04$).

Reaction times. The main effect of group ($F(1,61) = 17.79$, $p < 0.001$, $\eta^2 = 0.23$) was statistically significant, as typical readers were overall faster at naming compared with dyslexic readers (Table 2).

The main effects of object configuration ($F(1,61) = 106.37$, $p < 0.001$, $\eta^2 = 0.64$) and visibility ($F(1,61) = 16.35$, $p < 0.001$, $\eta^2 = 0.21$) were statistically significant and mirrored the accuracy data, as well as the two-way interaction between object configuration and visibility (F(1,61) = 20.55, $p < 0.001$, $\eta^2 = 0.25$), indicating that the participants were slower in the blurred version of "internal detail" objects (vs. non-blurred). Interesting, as illustrated in Figure 3, this effect was modulated by the factor group, as indicated by a statistically significant interaction group x object configuration x visibility ($F(1,61) = 7.74$, $p < 0.01$, $\eta^2 = 0.11$). Post hoc comparisons showed that participants from both reading groups were affected in objects that needed internal detail to be identified (longer RTs for "internal detail" objects vs. "global shape" objects, all *ps* < 0.05) and that dyslexic readers' performance (vs. typical readers) was especially impaired for blurred objects that needed internal detail to be identified. In fact, the naming advantage of typical readers over dyslexics was only statistically significant for blurred objects in which several parts or features needed to be encoded for recognition ($p < 0.01$; for non-blurred, $p = 0.31$), while groups did not differ statistically in naming "global shape" objects (blurred, $p = 0.19$, non-blurred, $p = 0.09$).

Table 2

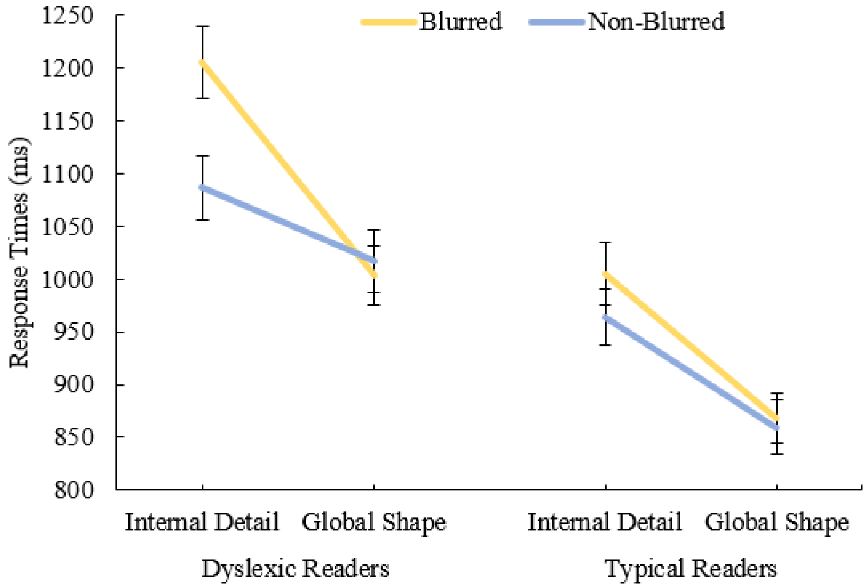
Mean Correct RT for Object Configuration (Global Shape and Internal Detail) and Visibility (Blurred and Non-Blurred), for Dyslexic and Typical Readers

Groups	Object Configuration		Object Visibility	
	Global Shape	Internal Detail	Non-Blurred	Blurred
Dyslexic Readers	1010.42 (27.69)	1145.84 (30.51)	1051.94 (28.24)	1104.32 (28.75)
Typical Readers	863.66 (23.98)	984.90 (26.42)	911.95 (24.46)	936.61 (24.90)

Note. RTs are presented in ms. *SE*s are presented in parentheses.

Figure 3

Mean Correct RT for the Two Reading Groups (Dyslexic and Typical Readers) in Terms of Object Configuration (Global Shape vs. Internal Detail) and Visibility (Blurred vs. Non-Blurred)



Discussion

The results from Experiment 1 showed that dyslexic readers, like typical readers, are more accurate and faster at naming objects that could be recognized from their global shape compared to objects for which recognition relies on the internal detail and, as expected, adding blurring to the object images was detrimental for performance in both groups. The fact that dyslexic readers were as accurate in naming the objects as typical readers suggest that they had no difficulties with the task in general. Interesting, the triple interaction found for RTs indicated that naming blurred “internal detail” objects was especially hard for dyslexic readers compared to the typical readers, while both groups were equally fast at naming “global shape” objects regardless of their visibility. Of note, this pattern was not caused by differences in the visual ambiguity of the objects (and, specifically, a larger ambiguity in the “internal detail” objects), given that both conditions were matched for that variable. Hence, from the present experiment, it seems that dyslexic readers can use global shape information for object identification, but, however, are less efficient at recognizing where internal detail is needed, which might suggest that they are poor at using part-based processing during object recognition.

In order to confirm and extend these results, in Experiment 2 we studied object recognition by using two different classic object identification tasks and different stimuli, that tap into different stages of visual object processing (Humphreys et al., 1988; Humphreys et al., 1999). This experiment was also designed to eliminate the possibility that the observed results might rather be explained by the low spatial frequency content of the blurred object images. The processing of low spatial frequencies depends on the functioning of the magnocellular system (dorsal stream of the visual cortex), that in turn has been argued to be impaired in dyslexic readers (Stein, 2001, 2018, 2019). We think, however, it is unlikely that the results in the current studies are caused by such an impairment, as the results revealed a triple interaction. If this was the case, then dyslexics would have been expected to show difficulties in the blurred “global shape” condition as well, which was not the case. Nevertheless, in order to validate our results, we decided to conduct two classic tasks (including the exact same items) that have been shown to be (probably) based on the local shape information and the global shape information to a different extent (e.g., Gerlach, 2017; Gerlach & Poirel, 2018).

Experiment 2

A superordinate object categorization and a difficult object decision tasks were constructed, modeled by Gerlach and Poirel (2018). In the object categorization task, participants had to decide whether an object presented was a natural object or an artifact (i.e., a superordinate classification). In the object decision task, participants had to decide whether the object presented was a real object or a (chimeric) non-object. It is usually found that the object decision task is more difficult to perform than the superordinate categorization task, and the assumption is that it requires less object individuation to classify an object at a superordinate level than it does to decide whether it represents a real object or a chimeric non-object (Gerlach et al., 2000; Gerlach, 2017). Gerlach and Poirel (2018) examined the relationship between performance on a classical task normally used to study local and global processing styles (i.e., Navon task) and these two visual object processing tasks. The results suggested that the categorization task involves global processing and the decision task involves a more local type of processing.

In the superordinate categorization task, natural objects are harder to differentiate perceptually because these objects tend to be globally more visually similar with other members of their categories compared to artifacts (Gerlach et al., 2000). However, if one assumes that information processing operates in a cascade mode (Humphreys et al., 1988), on the categorization task evidence for superordinate category membership accumulates at a semantic level, while structural processing takes place, thereby compensating for the difference between the two object categories (natural objects and artifacts) with respect to perceptual differentiation (Gerlach et al., 2000). On the other hand, in the difficult object decision task, the non-objects were chimeric, which means that they were composed of different parts from real objects. It is conceivable that the inclusion of chimeric non-objects favors the use of a more local processing (Gerlach & Toft, 2011). In fact, a high demand perceptual differentiation is needed (Gerlach & Toft, 2011), as a local and more detailed processing of the components of the chimeric non-object is required and it is the integration of all the real parts that make the (non-)object impossible.

If, as we assumed, the observed differences between groups in Experiment 1 are about suboptimal local processing, then results should converge, i.e., dyslexic readers' performance (vs. typical readers) were expected to be especially impaired when the task relied more upon local shape information in Experiment 2, that is, in the object decision task.

Methods

Participants. A sub-sample of participants from Experiment 1 took part in this new experiment. This sub-sample included 16 adults with dyslexia (10 females) and 16 typical readers (12 females), matched on years of education, age, and nonverbal IQ (all *ps* > 0.1). The demographic variables and mean performances of both groups of readers on cognitive and literacy measures can be seen in Table 3.

Table 3

Demographic Variables and Average Performance on Cognitive and Literacy Tests of Dyslexic and Typical Readers, and Group Differences (t-test)

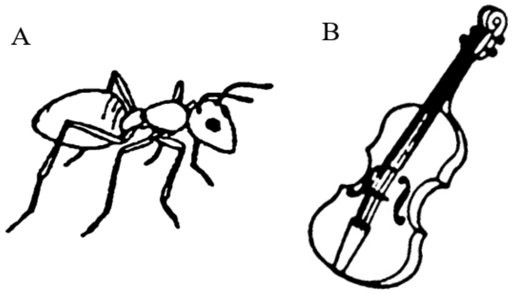
Variables	Dyslexic Readers (N = 16)	Typical Readers (N = 16)	*t-value*
Age	22.06 (2.99)	24.50 (5.32)	1.60
Years of Education	13.75 (1.95)	14.94 (1.88)	1.76
Matrix Reasoning	11.63 (2.85)	12.88 (1.71)	1.51
3DM (Items/Sec)	1.18 (0.27)	1.89 (0.26)	-7.49*
1-Min TIL (Max.= 36)	9.38 (2.66)	15.75 (2.67)	-6.77*

Note. SD are presented in parentheses. *$p < 0.001$

Materials. For the object categorization task, 60 pictures of real objects were used (black and white line drawings). These objects were selected from the set by Snodgrass and Vanderwart (1980) and comprised 30 natural objects and 30 artifacts (see Figure 4 for an example). The two sets of objects were matched for visual ambiguity and familiarity (Ventura, 2003) and visual complexity (Szekely & Bates, 2000) (*t*-tests, all *p*s > 0.2).

Figure 4

Example Display of One Trial of the Object Categorization Task

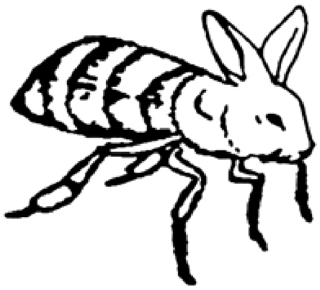


Note. A. Natural Object Condition; B. Artifact Condition.

For the object decision task, 120 pictures were used: 60 real objects and 60 chimeric non-objects. The real objects in this task were the same objects which were used in the object categorization task allowing for a direct comparison of items across tasks (following prior studies, e.g., Gerlach & Poirel, 2018). The 60 chimeric non-objects are line-drawings of closed figures constructed (as much as possible) by exchanging parts belonging to objects from the same category (Figure 5). These non-objects were composed of parts from objects that were not used as real objects.

Figure 5

Example of a Chimeric Non-Object (Bee + Rabbit) Used in the Object Decision Task



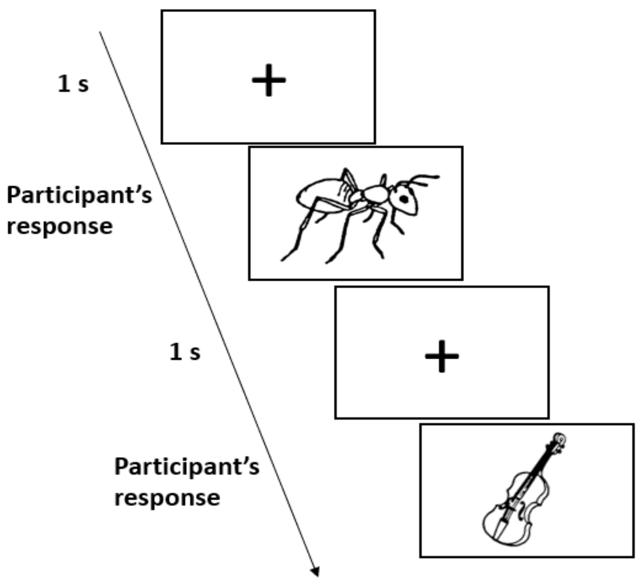
Experimental Procedure. In the object categorization task, participants were seated in front of a computer screen and were instructed that they would be shown pictures and had to decide whether they depicted natural objects or artifacts. A fixation cross "+" appeared at the center of the screen for 1s, followed by the presentation of the picture of the object (500 x 362 pixels) that stayed on the screen until the participant made a response (Figure 6). There was an opportunity to rest after 30 trials (until the participant was ready). There were two sets available, balanced among the participants in each group, in which we counterbalanced the hand of response. In set 1, participants were instructed to press a green key (green sticker in respective key) if the picture depicted an artifact and a red key (red sticker in respective key) if it depicted a natural object, or vice versa in set 2; each participant performed only one of the sets.

In the object decision task, participants were seated in front of a computer screen and were instructed that they would be shown pictures and had to decide whether they represented a real object or a non-object. The sequence of events was the same as for the categorization task (Figure 6); participants could rest after each 40 trials (until the participant was ready). The hand of response was counterbalanced in two sets, following the same procedure as for the categorization task.

Before each task, participants performed 15 practice trials to familiarize with the experimental task. In both tasks, the order of pictures was pseudorandomized. All stimuli were presented centrally on a white background on a computer screen and subtended 5-7° of visual angle. The order of presentation of both tasks was also counterbalanced among the participants in each group.

Figure 6

Sequence of Events in the Object Categorization and Decision Tasks



Results

Mean percentage of accuracy and the mean correct RT were calculated for each task. First, the data was trimmed by excluding RT which fell above/below 3 SD from the subject and condition means.

In order to analyze the effect of task for the exact same objects and given that the purpose of the non-objects in the object decision task was only to encourage detailed shape processing of the real objects, the analyses for the object decision task were based on correct responses to real objects only (Gerlach & Toft, 2011). The significant differences for the different tasks and for each group were tested with repeated measures ANOVAs, including the task (object categorization vs. object decision) as within-subject factor and the group as a between-subject factor (dyslexic readers vs. typical readers). Post-hoc analyses (Tukey HSD) were conducted to investigate significant interactions.

Accuracy. Both group of readers performed close to the ceiling in both tasks (Table 4), reaching more than 95% of correct responses in the object categorization task and more than 90% of correct responses in the object decision task, and the groups did not differ significantly (object categorization: $F < 1$; object decision: $t(30) = -0.10$, $p = 0.92$). Accordingly, accuracy was not analyzed further.

Table 4

Mean Percentage Accuracy for the Object Categorization and Object Decision Tasks, for Dyslexic and Typical Readers

Groups	Categorization Task		Decision Task
	Natural Objects	Artifacts	Real Objects
Dyslexic Readers	95 (2.17)	96.88 (0.97)	94.27 (1.47)
Typical Readers	96.46 (2.17)	98.54 (0.97)	94.48 (1.47)

Note. *SE*s are presented in parentheses.

Reaction times. Before the main analysis including the factor task, we ensured that there was no interaction between the factor group and the stimulus category (natural objects vs. artifacts) in the object categorization task. A repeated measures ANOVAs confirmed it. The main effect of group was statistically significant ($F(1,30) = 6.84$, $p = 0.01$, $\eta^2 = 0.19$), as typical readers (vs. dyslexic readers) responded faster, but there was no interaction between group and stimulus category ($F(1,30) = 1.85$, $p = 0.18$, $\eta^2 = 0.06$), meaning that both groups of readers showed the same pattern of performance. As expected, the main effect of stimulus category ($F(1,30) = 8.35$, $p < 0.01$, $\eta^2 = 0.22$) indicated that both groups of readers showed faster responses when the object represented a natural object (dyslexics: *M* = 7345.66; *SE* = 275.59; typical readers: *M* = 6422.09; *SE* = 275.59) than an artifact (dyslexics: *M* = 7992.65; *SE* = 366.13; typical readers: *M* = 6654.92; *SE* = 366.13).

We then proceeded for the main analysis including the factor task. The main effect of group ($F(1,30) = 13.14$, $p = 0.001$, $\eta^2 = 0.31$) was statistically significant, as typical readers were faster overall (Table 5). The main effect of task was also statistically significant ($F(1,30) = 54.56$, $p < 0.001$, $\eta^2 = 0.65$), with both groups of readers being faster at deciding in the categorization task than in the object decision task. As illustrated in Figure 7, the interaction group x task was also significant (F(1,30) = 5.04, $p = 0.03$, $\eta^2 = 0.14$). Post hoc comparisons confirmed that both reading groups were slower in the object decision task (vs. categorization task; both *ps* < 0.01). However, this difference between tasks was significantly larger for the dyslexic participants ($M_{diff} = 1985$, SD = 1112) than for the typical readers ($M_{diff} = 1060$, SD = 1218; $t(30) = -2.24$, $p = 0.032$). More interesting, comparisons between groups also revealed that the groups differed statistically in the object decision task ($p < 0.001$), because dyslexic readers exhibited significantly longer RTs than the typical readers, but not in the object categorization task ($p = 0.11$).

Table 5

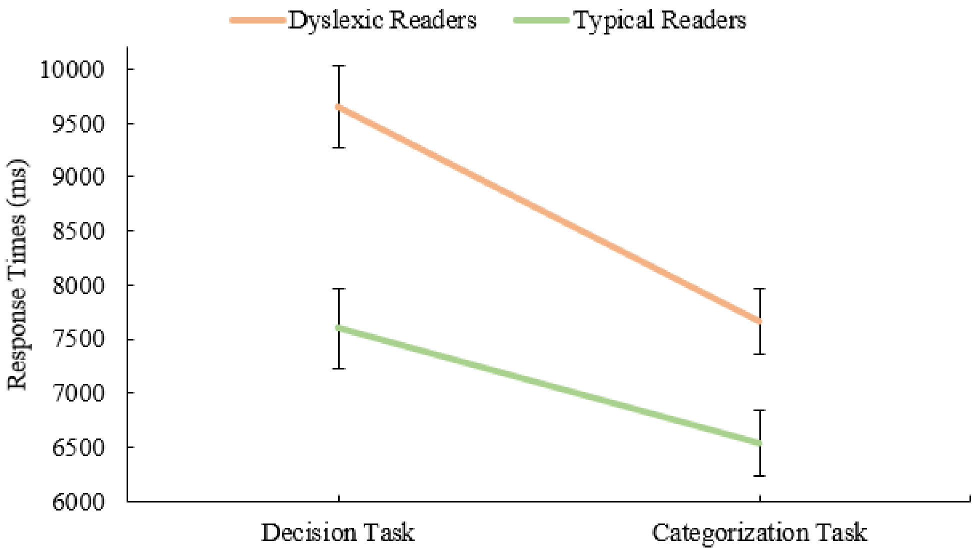
Mean Correct RT for Objects in the Object Categorization and in the Object Decision Task for Dyslexic and Typical Readers

Groups	Categorization Task	Decision Task
Dyslexic Readers	7669.16 (305.63)	9654.63 (377.26)
Typical Readers	6538.51 (305.627)	7598.33 (377.26)

Note. *SEs* are presented in parentheses.

Figure 7

Mean Correct RTs for the Two Reading Groups in the Object Decision and Categorization Tasks



Discussion

The results from Experiment 2 showed that, in a superordinate classification task, both groups of readers were faster at responding to natural objects than to artifacts, as expected (e.g., Riddoch & Humphreys, 1987, cited by Humphreys et al., 1999). Humphreys et al. (1999) discuss this result in terms of an advantage for perceptually similar stimuli, in tasks that tap into semantic knowledge, because objects that belong to the same category are typically more similar in shape than objects that belong to different categories. In fact, natural objects tend to have high levels of perceptual similarity across their exemplars relative to artifacts (Gerlach et al., 2000). In our task, the effect of stimulus category (natural objects vs. artifacts) was not modulated by the factor group. Therefore, any possible interaction between type of task (object categorization vs. object decision) and group (dyslexics vs. typical readers) is not confounded by group differences in processing natural objects and artifacts.

More important, a main result from Experiment 2 was the finding that although both groups of readers were slower in the object decision task than in the categorization task, this difference was significantly larger in the dyslexic group. Moreover, relative to controls, the performance of the dyslexic group was particularly poor in the object decision task, as they showed significantly longer RTs in this task, while groups were equally fast in the classification task (at least statistically). We interpret these results as consistent with those obtained in Experiment 1 using a different task and different manipulations of visual objects, i.e., dyslexic readers seem to have difficulties when object recognition requires processing individual components or parts.

General Discussion

A number of studies have suggested that written letter and word processing may not be the same for dyslexic and normal readers, as the former group seems to show suboptimal processing of local information. This is suggested, for example, by their effortful letter-by-letter reading (e.g., Araújo et al., 2014), a lack of a dissociation between letters and nonletters in the CE (e.g., Fernandes et al., 2014; Lachmann & van Leeuwen, 2008a, 2008b) and a greater improvement in text reading when crowding was reduced (e.g., Zorzi et al., 2012). The aim of this thesis was to explore whether the hypothesized difficulties in part-based processing in dyslexia extend beyond letters and visual words, influencing the processing of non-linguistic objects. To do so, performance during object recognition was explored in dyslexic adults and age-matched typical readers. In Experiment 1, we orthogonally manipulated the configuration of the objects (objects that could be recognized from their global shape vs. objects whose recognition depended on their internal detail) and their visibility (blurred vs. non-blurred). In Experiment 2, we rather manipulated the type of task used, examining the participants' performance to the same objects under either a difficult object decision task or a superordinate object categorization task which presumably requires less object individuation (e.g., Gerlach et al., 2000; Gerlach & Toffu, 2011). The rationale in this experiment was that when the task encourages the codification of parts and their integration in a whole, as in the case of chimeric non-objects decision, and it is not possible to predict whether the next stimuli is a real object or a non-object, decision performance is (in principle) achieved by a predominant local processing strategy (a similar logic could explain the modulation of non/word length effects by list composition, e.g. Lima & Castro, 2010). Hence, local shape would play a more important role in object decision task than in superordinate categorization. Our results from different object manipulations and tasks were convergent.

In both experiments, the accuracy results did not show significant differences between the two reading groups. This was not surprising as difficulties by dyslexic readers are more often reflected in terms of longer RTs, both with linguistic (e.g., Araújo et al., 2014) and non-linguistic stimuli (e.g., Araújo & Faísca, 2019). This result is also predicted from the fact that we sampled adults with years of print exposure (even dyslexic readers), hence, we may assume that participants knew all the (familiar) object images used and had a large vocabulary available that can assist their performance (it is well-known that vocabulary increases with age and print exposure, e.g., Kirby et al., 2008). Thus, the fact that we found group differences in RTs but not in accuracy suggests that the performance of dyslexic readers is mainly related to the speed and efficiency with which the object recognition system handles information.

The results regarding RTs, in turn, seem to suggest that dyslexic readers have difficulties specifically at coding part-based information for the identification of objects. This was suggested across tasks that tap into the different stages of visual object processing (Humphreys et al., 1988; Humphreys et al., 1999): the object decision task taps into the structural description system, the object categorization task taps into the semantic system, and the visual naming task taps into the phonological system. Specifically, relative to controls, dyslexic readers' performance was especially poor (longer RTs) for those objects that required attention to parts and internal features for their recognition (e.g., zebra), exacerbated under difficult encoding contexts (blurred images; Experiment 1), and in a task where (presumably) a coarse global shape processing strategy did not suffice for successful object recognition and consequently participants needed to base also on local shape information (i.e., object decision task; Experiment 2). The fact that in Experiment 2, despite being the exact same objects, both group of readers were slower in the object decision task than in the categorization task (with the difference between tasks being larger for the dyslexics) is in line with the assumption that a more complex process was happening in the object decision task (e.g., binding local and global shape information prior to decision).

The current results from Experiments 1 and 2 agreed with results from recent studies on face and object processing. For example, Sigurdardottir et al. (2015, 2019) found problems in local processing of faces in dyslexic readers, using a composite face paradigm and a feature-based face matching task. Difficulties in object recognition tasks that require the individuation of exemplars within a category of objects were also found (Sigurdardottir et al., 2015).

The results of the current study and these prior studies could be explained by the neurodeficits underlying dyslexia. Sigurdardottir and colleagues (2021) argued that dyslexia is a disorder related with high-level vision processes (i.e., visual processes that are dedicated to analyzing the structure of our surroundings), supported by higher levels of the ventral visual stream. Indeed, when compared with typical readers, readers with dyslexia often show a hypoactivation in regions of the left ventral occipito-temporal cortex in response to written stimuli (Martin et al., 2016; Richlan et al., 2011) and also to pictures of objects (McCrory et al., 2005), and a reduced left occipitotemporal N170 ERP tuning for visual letters (Mahé et al., 2012). In turn, neuroimaging studies and studies with clinical evidence (e.g., Yamaguchi et al., 2000; Robertson & Lamb, 1991) suggested that local parts information is preferentially processed in the left hemisphere, while global shape information is preferentially processed in the right hemisphere. A study by Tso et al. (2020) found that dyslexic readers had stronger holistic processing (assessed using the composite paradigm) and weaker left side biases (assessed using mirror-symmetric Chinese characters) in Chinese character perception than age-matched controls; expertise for Chinese characters is associated with decreased holistic processing and a stronger left side bias (Hsiao & Cottrell, 2009). So, the difficulties encountered in local processing by dyslexic readers could be associated with a dysfunction in regions in the left ventral cortex.

These difficulties seem to contrast with an advantage in global processing during object processing. It has been argued that dyslexics might compensate their difficulties and hypoactivation in left regions of the brain to letters by developing “stronger” right hemispheres (Stein, 2018, 2019), which is in line with the neuroimage studies mentioned previously (i.e., global information is preferentially processed in the right hemisphere; e.g., Robertson & Lamb, 1991; Yamaguchi et al., 2000). This could explain the global processing advantage sometimes encountered in dyslexic readers, for example, at recognizing impossible geometric figures (i.e., figures made of possible parts but that when integrated result in an impossible figure; e.g., von Károlyi, 2001; von Károlyi et al., 2003). Supporting this idea is also a study by Mayseless and Breznitz (2011) in which dyslexic and typical readers performed an object decision task during ERPs recordings. Compared to typical readers, dyslexics exhibited significantly shorter latencies of P1 and P2 ERP components to both real and pseudo-objects. The authors speculated that such results could reflect a more global processing style used by the dyslexic readers. On the other hand, studies have also suggested that holistic processing of faces (as typically seen and supported by the right hemispheric fusiform gyrus; Dehaene & Cohen, 2011; Farah et al., 1998) is intact in dyslexic readers (Sigurdardottir et al., 2015, 2019).

Finally, we cannot exclude the possibility that the observed difficulties by dyslexic readers are not related with deficits in (local, part-based) perceptive processing but rather with visual attentional deficits or difficulties in task-switching (e.g., Hari & Renvall, 2001; Stein, 2019). Stein (2001, 2018, 2019) argued that the development of the magnocellular system in the dorsal stream of the visual cortex (involved in visual attention and visuomotor control) is impaired in dyslexic readers, explaining the deficits usually encounter in poor temporal processing. In our Experiment 1 we found that blurring was especially detrimental for dyslexic readers while recognizing "internal detail" objects. As already mentioned, blurring alters image information such that fine, local information (conveyed by low spatial frequencies) is reduced. However, we think it is unlikely that our results are explained by reduced contrast sensitivity for low spatial frequencies (which rely on the functioning of the magnocellular system; Stein, 2001, 2018, 2019) in readers with dyslexia. If so, then the dyslexic group should have also been impaired in blurred "global shape" objects, which was not the case. Moreover, the results from Experiment 2 support our interpretation of local processing difficulties in dyslexia, given that we found convergent results by using different tasks and non-blurred object images.

On the other hand, difficulties in shifting attention between different tasks has also been proposed. For example, the "sluggish attentional shifting" hypothesis proposes that dyslexic readers' attention, once engaged, cannot easily disengage (and vice versa; Hari & Renvall, 2001). By default, an object is first processed globally and then by parts (e.g., Leek et al., 2016). So, it might be the case that the dyslexic readers struggle in shifting between the global and local parts in object recognition (rather than having a deficit in the local processing per se). In fact, a few studies have suggested that dyslexic children are less able to flexibly switch between multiple tasks or strategies (e.g., connect circles containing numbers or letters randomly distributed, alternating between numbers and letters; color- and shape-matching task with cues that could imply a task switch or a task repetition), compared with typical readers and children with other developmental disorders such as autism (Moura et al., 2014; Poljac et al., 2010). The design of the present study doesn't allow to clarify whether or not a presumably larger switching costs in dyslexic readers could have contributed the response pattern observed; this hypothesis needs to be addressed in future research.

Regarding limitations of the present work, it is worth mentioning the small sample used, and in particular, the size of the sub-sample of participants in Experiment 2. These results warrant cautious interpretation, while emphasize the importance of carrying out more studies in this population comparing local and global processing in object recognition. Consequently, in our study the group of dyslexic readers was treated in a homogeneous way, although there is evidence suggesting processing differences between different subgroups of dyslexics. For example, Goldstein-Marcusohn and colleagues (2020) observed that the slowness of the "rate-specific" subtype of dyslexia was associated with a more part-based reading, while the fast and inaccurate profile of the "accuracy-specific" subtype of dyslexia was associated with a greater use of global processing. Thus, the results of the current study could have been different if this heterogeneity in dyslexia was considered. Also, our study cannot answer about the temporal course of global and local processing during object recognition in dyslexic vs. typical readers, which would be more informative about underlying processes. In fact, a study using EEG, which has a high temporal resolution (i.e., it provides a continuous measurement of changes over time, rather than a single timing measure; Ward, 2015), was planned for this thesis, but unfortunately was not accomplished due to the restrictions related to the COVID-19 pandemic.

In practice, it is possible that detecting impairments in visual object recognition could be used for early diagnosis of dyslexia. For example, there are neuropsychological batteries for dyslexia screening in which visual object naming tests are included (e.g., Wolf & Denckla, 2005). The present results highlight the potential utility of including objects that depend on their internal detail for recognition, as these seem to be particularly sensitive to detect differences between groups of readers.

Conclusion

In summary, in the present study we found novel evidence suggesting that difficulties in part-based (local) processing by dyslexic readers are not domain-specific but extends to other categories beyond written letters/words such as objects. One acknowledges that it is difficult to determine whether local processes that supported performance with “internal detail” objects are the same as those involved in the decision of real/non-real chimeric objects. Even so, our results converged, suggesting that the very different tasks and stimuli used may be taping into common underlying mechanisms for the processing of local information. Global processing, in turn, seems to be intact in dyslexia. No other study that we are aware of has explored local and global processing in the dyslexic population by using tasks that tap into all stages related to object recognition. Nevertheless, we argue that the most convincing evidence will have to come from complementary designs. Lastly, we note that the current study does not allow a causal direction to be established. One possibility is that a lack of reading experience could account for the observed differences in processing style, given that literacy acquisition and experience influence visual processing, and specifically, enhance a more local or parts-based style in visual processing of (non)linguistic stimuli (e.g., Malik-Moraleda et al., 2018; Ventura et al., 2013). Based on this literature, one could question if our results could be a consequence of a poor literacy experience in dyslexics (despite both groups of readers having the same years of formal education).

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