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RESEARCH PAPER

Cognitive subtyping of university students with dyslexia in a semi-transparent orthography: what can weaknesses and strengths tell us about compensation?

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Abstract Developmental dyslexia is characterized by a profile of reading- and writing-related difficulties which stands out as a core deficit in phonological processing. Although these difficulties seem to persist into adulthood, it is still an open question to what extent they are immune, or not, to the extensive training resulting from extended schooling. The main objective of this study was to explore the heterogeneity of the cognitive profile of European Portuguese highly literate adults with dyslexia. Thirty-one university students diagnosed with dyslexia during childhood and their matched skilled adult control readers were assessed through a battery of reading and cognitive tests. A cluster analysis of data obtained from participants with dyslexia identified two profile groups. While Cluster 1 grouped participants with clear phonological deficits and concomitant reading difficulties, Cluster 2 showed better performance on most of the core skills associated with reading and also better general cognitive abilities, suggesting that these dyslexic readers have partially resolved their phonological constraints along the development, probably due to the systematic exposure to reading and writing. As Cluster 2 matched typical readers in general cognitive abilities, it might also be the case that cognitive strengths associated with general intelligence worked as protective factors, helping students to strategically compensate for their reading difficulties. Overall, these results suggest that both mechanisms–partial remediation of the core phonological deficit and adoption of compensatory strategies supported by general cognitive skills–might contribute together to improving the reading performance of highly literate adults with dyslexia.

Keywords Reading disorders · Dyslexia · Cognitive subtypes · European Portuguese orthography · University students · Compensatory mechanisms

Introduction

Developmental dyslexia (henceforth, dyslexia) is a neurobiological disorder characterized by specific difficulties in accurate and/or fluent word recognition and by poor spelling and decoding abilities, despite

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adequate intelligence and the absence of general learning problems (Lyon et al., 2003; The International Dyslexia Association, 2014). It is primarily attributed to a phonological processing deficit (Ramus, 2003; Ramus & Szenkovits, 2008; Saksida et al., 2016), nevertheless, there is no doubt that dyslexia is multicausal (e.g., Lachmann et al., 2005; Pennington, 2006) and other suggested causes have been extensively debated (deficits in letter-speech sound integration: Blomert, 2011; impaired temporal sampling of speech: Goswami, 2011; inadequate implicit auditory regularity detection: Ahissar, 2007; impaired processing of brief sounds: Tallal & Piercy, 1973; visual dysfunctions: Bosse et al., 2007; or more general deficits in magnocellular functions: Livingstone et al., 1991; attentional mechanisms: Shaywitz & Shaywitz, 2008).

Typically, dyslexia is identified early during reading acquisition in childhood and the detected difficulties persist throughout life (Hatcher et al., 2002; Pammer, 2014; Swanson & Hsieh, 2009; Undheim, 2009). Indeed, a recent meta-analysis by Reis and colleagues (Reis et al., 2020) described that adults with dyslexia still exhibit markedly poor performance on almost all reading and writing tasks (reading words and pseudowords, text reading, and spelling, with relatively smaller effect sizes for reading comprehension), and continue having difficulties in phonological awareness (detection and manipulation of the sounds of spoken words, especially at the phonemic level), phonological short-term memory and verbal working memory (temporary storage and manipulation of phonological representations), and rapid automatized naming (quick access and retrieval of phonological representations stored in long-term memory). These difficulties have often been identified as deficient in children with dyslexia (Araújo & Faísca, 2019; Melby-Lervåg et al., 2012; Vellutino et al., 2004), and hence, might represent core deficits in dyslexia that hold along the developmental trajectory. In addition, it has been reported that children and adults with dyslexia are more likely to exhibit deficits in orthographic processing (e.g., Araújo et al., 2015; Kemp et al., 2009; Marinelli et al., 2009), in general cognitive skills (especially in speed of processing; Reis et al., 2020), and a general visual attention span disorder (Lobier et al., 2012; Valdois et al., 2003). However, there is limited knowledge on how cognitive development, successive years of formal schooling, and long exposure to print may affect the putative long-term stability of the dyslexia profile. Therefore, it is still an open question to what extent the deficits that characterize dyslexia are immune, or not, to the training resulting from extended schooling.

Indeed, it is known that manifestations of dyslexia can change across development, either due to compensation mechanisms and better metacognitive strategies or/and because of resolving deficits in older ages (for a discussion, see Cavalli et al., 2017; Eloranta et al., 2019; van Viersen et al., 2019). Furthermore, the probabilistic and multifactorial etiological models for dyslexia (e.g., Pennington, 2006) emphasize the multiple-deficit nature of this disorder, arguing that it has heterogeneous cognitive characteristics not exclusively related to the phonological core deficit (Pennington et al., 2012; Vidyasagar & Pammer, 2010). Thus, individual differences in reading trajectories and reading outcomes may also reflect different cognitive profiles that either hamper or benefit the adaptation of children with dyslexia to the reading and writing demands throughout schooling.

An additional, important constraint in the developmental trajectory of dyslexia is the linguistic environment, namely the degree of transparency with which symbols (graphemes, in alphabetic systems) represent sounds (phonemes). Several studies with a cross-linguistic design have found that orthographic transparency modulates the predictors of dyslexia status and the magnitude of the associated cognitive deficits both in children and adults (e.g., Landerl et al., 2013; Paulesu et al., 2001). Reis et al. (2020) meta-analytic results showed that in adulthood, deficits in (non)word reading and spelling are less severe, and phonological awareness may be less of a hurdle in transparent orthographies (i.e., with simple isomorphic letter-sound mappings such as in Finnish and Italian) than in opaque orthographies (such as in English), especially for speed measures. However, the impact of orthography on the heterogeneity and prevalence of dyslexia subtypes within a linguistic population has been far less explored (see, for an exception, Bergmann & Wimmer, 2008; Sprenger-Charolles et al., 2011). In a review of multiple-case studies conducted with English-, French- and Spanish-speaking children, Sprenger-Charolles et al. (2011) concluded that the degree of the transparency of the orthography modulates the prevalence of the dyslexia subtypes (phonological versus surface versus mixed subtypes). Bergann and Wimmer (2008) found that the proportion of surface and phonological dyslexia cases among German-speaking adolescents (a transparent orthography) was exactly the opposite of what was found in English-based studies. To our knowledge, no studies looked at the long-term impact of orthography on the heterogeneity of adult dyslexia subtypes.

Meta-analytic, as well as primary empirical studies comparing dyslexic and typical readers, have mostly taken a variable-centered approach, examining whole-sample averages or correlations between variables (e.g., Reis et al., 2020; Suárez-Coalla & Cuetos, 2015; Ziegler et al., 2003). Such an approach is particularly limited when attempting to conclude about individuals or specific groups of individuals. Alternatively, a person-centered approach examines the relationships among variables at the individual level, allowing the identification of specific patterns that are otherwise collapsed in variable-centered analysis. Characterizing the individual cognitive profile of adults with dyslexia may help to elucidate if a specific combination of cognitive skills might explain why their reading and writing difficulties persist or, alternatively, have been surpassed across development (see, for example, van Viersen et al., 2019). A considerable effort has been invested in subtyping children with dyslexia (e.g., Chung et al., 2010; Hedman, 2012; Heim et al., 2008; King et al., 2007; Pacheco et al., 2014; Sprenger-Charolles et al., 2011; Tobia & Marzocchi, 2014; Willems et al., 2016; Zoubrinetzky et al., 2014), whilst cognitive subtyping of adults has been scarce, despite the developmental nature of dyslexia and the growing number of dyslexic students in higher education institutions (Pino & Mortari, 2014). To fill this gap, the main objective of the present study is to explore the heterogeneity of the cognitive profile in a sample of European Portuguese highly literate adults with dyslexia. European Portuguese is a medium complexity level orthography with highly consistent grapheme-to-phoneme correspondences but low consistency in phoneme-to-grapheme mappings (Serrano et al., 2011).

University students are an interesting population to investigate the long-term manifestations of dyslexia since these students, who were diagnosed with dyslexia early in school, have been systematically exposed to reading and writing demands for more than twelve years. Considering their successful academic path, these so-called high-functioning individuals were expected to have (at least partially) overcome such demands. Particularly relevant is the possibility that specific cognitive profiles may have helped some of them to surpass their difficulties. For example, a recent longitudinal study (Eloranta et al., 2019) showed that rapid automatized naming (RAN) skills in childhood differentiated adult dyslexic individuals with a persisting reading disorder from those with improved reading fluency. This result suggests that less severe deficits in specific cognitive skills involved in reading acquisition may help children to partly resolve their difficulties during development. Arguably, the characteristics of the orthographic systems can contribute to it. Another possibility is that compensatory strategies based on protective generic cognitive factors, develop along with the developmental trajectory, and hence, contribute to a compensated reading performance, even if the underlying reading-related cognitive deficits persist.

Thus, two main distinct theoretical perspectives have been discussed in the literature about resolving versus persistent groups of dyslexia. One, the *core-deficit view* (Stanovich & Siegel, 1994), suggests that reading level performance is fully determined by the severity of the core deficits that characterize dyslexia (phonological awareness, RAN, and verbal short-term memory). More general cognitive skills strongly associated with intelligence cannot compensate for the core deficits of this disorder. According to this view, resolving literacy difficulties will be essentially associated with the attenuation of dyslexia core deficits through development. On the other hand, according to the *twice-exceptionality view* (Foley-Nicpon et al., 2011), the presence of more general cognitive strengths relevant to literacy (e.g., vocabulary, language comprehension, general IQ) will work as protective factors that positively influence dyslexics' literacy level by supporting the development of compensatory strategies that might decrease the impact of underlying deficits.

In sum, although substantial efforts have been made to characterize dyslexia at primary and secondary school, more information is needed about the long-term outcomes of this disorder, specifically from a person-centered perspective. Despite the growing number of studies on adults with dyslexia (see, for instance, the meta-analytic studies by Reis et al., 2020, and Swanson & Hsieh, 2009), there is still "a need for scientific evidence about the cognitive subtypes of students with dyslexia in higher education, particularly for non- English-speaking countries" (Callens et al., 2012, p. 1). Thus, this study aims to get an insight into the cognitive subtypes of adults with dyslexia in a semi-transparent orthography, the European Portuguese. Given the particularly strong association between poor phonological processing skills (phonological awareness and RAN) and reading failure in semi-transparent orthographies (Landerl et al., 2013; Reis et al., 2020), a higher proportion of adult dyslexic participants with this profile symptoms will be expected, likely corresponding to the most severely affected subtype. On the other hand, both compensation or remediation possibilities, in the long run, might result in the manifestation of other less affected subtypes (having, for instance, resolved the phonological core deficit or, alternatively, showing normative reading with the support of better general cognitive abilities).

Identifying the cognitive subtypes in adulthood may prove relevant in understanding the limits and possibilities of protective cognitive factors on dyslexia, and contribute to identifying the possible compensation mechanisms used by university students diagnosed with childhood dyslexia. Ultimately, such findings may be of relevance from a clinical and educational standpoint since they allow us to recognize the challenges that high-functioning adults with dyslexia have to face.

Method

Participants

Thirty-one adults diagnosed with dyslexia (21 females) and 31 adult controls without reading problems (19 females) participated in this study. All participants were university students and native Portuguese speakers, who had normal or corrected-to-normal vision and did not report neurological diseases, psychiatric disorders, or attention deficits. The groups were matched for age (dyslexics mean age ± SD: 25.3 ± 5.4 years; typical readers: 24.5 ± 6.2 years) and all participants have normal-range nonverbal IQ (scores above 85), as measured by the Wechsler Adult Intelligence Scale, WAIS-III (Performance Scale; Wechsler, 2008).

The participants with dyslexia were recruited through advertisements spread by e-mail and campus posters, as well as from the University Support Service for students with learning disabilities. All of them had received a formal dyslexia diagnosis by a specialized therapist during their childhood/adolescence[1] and still consider their reading speed and spelling inadequate. They also had a history of reading difficulties expressed by high scores in a self-report measure of reading history (Adult Reading History Questionnaire, ARHQ; Lefly & Pennington, 2000; Portuguese adaptation: Alves & Castro, 2005; scores above the cut-off point 35 indicate an increased likelihood of reading disorders). Empirical research has supported the use of ARHQ as a reliable tool for dyslexia screening, attesting to its high sensitivity, specificity, and overall correct classification of the reading status (Parrila et al., 2007; Welcome & Meza, 2019; with Portuguese samples: Alves & Castro, 2005). Control participants had no history of reading and/or spelling difficulties and exhibited reading scores in the normal range (higher than 1 SD below the expected mean level in the 1 min TIL measure; see below).

Measures

Participants completed a battery of reading and cognitive tests described below. In addition, all filled out a small sociodemographic and clinical questionnaire and completed the Portuguese adaptation of the Adult Reading History Questionnaire (ARHQ; Alves & Castro, 2005).

Reading

Tests of reading skills included a time-limited reading aloud task, adapted to the Portuguese adult population from the Differential Diagnosis Dyslexia Battery (3DM; Blomert & Vaessen, 2009; Portuguese version: Pacheco et al., 2014), and a silent reading test for reading comprehension (1-min TIL; Fernandes et al., 2017). In the 3DM reading fluency test, participants

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[1] The dyslexia diagnosis reports to which we had access to were very heterogeneous in terms of assessment protocols (e.g., the specific measures used to examine reading level) and the way results were reported. Given this heterogeneity, we consider that it was not informative to provide data obtained from previous dyslexia assessments.

were presented with three lists of written stimuli (high-frequency words, low-frequency words, and pseudowords) and had to read aloud as many stimuli as possible for 30 s. Scores correspond to the number of correctly read high- and low-frequency words (word reading fluency score) and pseudowords (pseudoword reading fluency score). In the 1-min TIL test, participants were required to read silently an incomplete sentence and to choose, among four options, the word that best fits into the context. The score corresponds to the number of correct responses produced in one minute (max. 36). Test–retest procedure provides a satisfactory index of reliability for TIL ($r = 0.71$; Fernandes et al., 2017).

Phonological processing

Phonological awareness was assessed using two tests (Francisco & Faísca, 2012). In the phoneme deletion task, participants had to repeat orally presented words after deleting a target phoneme (in initial, middle, or final position, e.g., “repeat/sangue/[blood] without/s/”); after deletion, all words would become pronounceable pseudowords. The score corresponds to the number of correct responses (max. 18). In the spoonerism task, participants had to swap the initial phonemes of two aurally presented words (“foca/dado” [seal/dice] becomes “doca/fado”, which still corresponded to real European Portuguese words). The score was the number of words correctly produced (max. 19 items × 2 words = 38 words).

Naming speed was assessed with two traditional serial RAN tasks (5 items × 10 repetitions; Alves et al., 2007). Participants had to correctly name an array of digits and letters as quickly as possible. Given the high correlation between the letter- and digit-RAN tasks ($r = 0.82$), a composite RAN alphanumeric score was obtained by averaging the number of correctly named items per second in both tasks.

Phonological short-term memory was assessed with the digit span subtest (forward version) of the WMS-III (Wechsler, 1997). The score was the number of correctly recalled series of digits.

Working memory

Verbal and nonverbal working memory was measured using the backward Digit Span subtest and.the Corsi block-tapping test, respectively (WMS-III; Wechsler, 1997).

Visual attention span

Visual attention span, the amount of distinct visual elements which can be processed in parallel in a multi-element array, was assessed using a five-consonant global report task (modeled by Valdois et al., 2003). Twenty random five letter-strings (e.g., R H S D M) were built up from 10 consonants. Strings contained no repeated letter and never matched a real word; letters were spaced to minimize lateral masking and the array subtended an angle of approximately 3.8°. Each letter string was displayed at the center of the screen for 200 ms, and participants had to report verbally as many letters as possible immediately after the string had disappeared. The task included 20 experimental trials, preceded by 10 practice trials where participants received feedback. Scores corresponded to the total number of letters accurately reported (identity, not location: max. 100).

General cognition

Nonverbal reasoning ability was assessed using the Block Design, Matrix Reasoning, and Picture Completion subtests of the WAIS-III Performance Scale (Wechsler, 2008), and processing speed was assessed with the Coding subtest from the same Scale.

The Vocabulary subtest of WAIS-III was used to examine expressive lexical knowledge and as a proxy for general language and listening comprehension skills (see Braze et al., 2016).

Procedure

Participants were assessed by a trained psychologist in a quiet room at the University campus. Assessment sessions last approximately 1,5 h. All participants gave their prior written informed consent in compliance with the Declaration of Helsinki.

Cluster analysis

Hierarchical cluster analysis was adopted to subtype adults with dyslexia; in this analysis, squared Euclidian distance and Ward’s agglomerative clustering method were used given their statistical advantages (as denoted in similar studies, e.g., Crews & D'Amato, 2009; Milligan & Cooper, 1987). As our goal was to differentiate cognitive subtypes, we used both reading fluency measures and phonological processing measures in the cluster analysis. The remaining variables were used to characterize a posteriori the clusters found.

To prevent level effects, all variables were converted to *z*-scores. Mahalanobis D2 distances were computed to confirm the nonexistence of multivariate outliers in the sample (*p* values associated with D2 were larger than 0.03 for all participants). Multicollinearity was evaluated through VIF (variance inflation factor), an indicator that, according to Hair et al. (2010), should be smaller than 5 to avoid including highly correlated variables as predictors. The stability of the cluster solution was assessed by resampling methods (Hennig, 2007): 1000 bootstrap samples were extracted from the original dyslexic sample, and clusters were obtained for each one through the same agglomerative clustering; bootstrap clusters and original clusters were compared for similarity based on the Jaccard coefficient (ranging from 0 to 1.00, total correspondence between clusters) to check for cluster overlapping; it is recommended that the average Jaccard coefficient should be higher than 0.60 (ideally, larger than 0.85) to indicate a stable solution across the 1000 bootstrap replications. The *R* fpc package was used to implement this validation procedure (Hennig, 2020).

When comparing the groups identified through cluster analysis, a non-parametric inferential approach was preferred due to the small and unbalanced group sizes (Mann–Whitney and Kruskal–Wallis tests). Accordingly, we used Vargha and Delaney's (2000) A_{12} as an effect size indicator, which is interpreted as a nonparametric estimate of the probability that a randomly chosen member from group 1 scores higher than a randomly chosen member from group 2. Thus, $A_{12} = 0.5$ indicates that both groups are equivalent. Following Vargha and Delaney (2000), a small effect size is expressed by $A_{12} = 0.56$; medium effect sizes occur when $A_{12} = 0.64$, and large effect sizes when the A_{12} probability is higher than 0.70.

Results

First, typical readers and readers with dyslexia were compared across the several domains considered (see Table 1). Adults with dyslexia performed systematically worse than typical control readers on all reading measures, with effect sizes being always very large (Cohen's $d > 1.7$), thus indicating a persistent clear deficit in the reading domain. The performance level in the 1-min TIL test (decoding and reading comprehension) was converted into *z*-scores with reference to a normative sample of 185 adult college students (mean age: 22.8 ± 5.3 years old; Fernandes et al., 2017). *z*-scores confirmed that all participants assigned to the control group scored in the average range (*z*-scores > -1), while participants with dyslexia showed *z*-scores ranging between -3.41 and 0.80 (10 of them obtained *z*-scores > -1). Thus, despite having a childhood dyslexia diagnosis and still recognizing their reading difficulties, some participants with dyslexia managed to reach normative levels on a reading comprehension test.

Poor performance in the phonological processing domain also characterized the dyslexic group. However, phonological deficit sizes were smaller comparatively to reading deficits ($0.62 \leq$ Cohen's $d \leq 1.76$), especially for verbal short-term memory (albeit still moderate-to-large, $d = 0.6$). In turn, slower naming speed was more marked than deficits in other phonological processing skills in dyslexia. Of note, not only were dyslexic adults impaired for alphanumeric RAN speed but some still committed errors during these tasks, unlike typical readers (especially in the RAN letters, where 11 dyslexia participants did not accurately name one or two of the 50 items). Group comparisons also showed that visual attention span ability (with verbal stimuli) was impaired in dyslexic participants. While we observed equivalent visuospatial working memory performance (Corsi blocks) for the dyslexic compared with the control group, this was not seen in the verbal modality, in which they performed worse than controls (backward digit recall, Cohen's $d \sim 0.7$). Considering general cognitive abilities, no significant group differences were apparent for nonverbal reasoning ability (Block Design and Matrix Reasoning) and processing speed (Coding), but yet, dyslexic participants showed lower Vocabulary scores than their controls (Cohen's $d \sim 0.5$).

Cluster analysis

Cluster analysis was used to identify profiles within the group of participants with dyslexia based on

Table 1 Descriptive for age, school years, reading, and cognitive measures for each reading group

	Readers with dyslexia (n = 31) M ± SD	Typical readers (n = 31) M ± SD	Cohen's *d*	*t*	*p*
Age	24.5 ± 6.18	25.3 ± 5.39	0.14	0.5	0.586
School years	14.9 ± 1.51	14.9 ± 0.93	0.03	0.1	0.920
ARHQ	61.4 ± 11.01	26.6 ± 8.63	− 3.52	− 13.9	< 0.001
Nonverbal IQ	107.4 ± 12.68	102.7 ± 9.76	− 0.41	− 1.6	0.109
Reading					
Word reading fluency (3DM)	76.6 ± 19.03	112.3 ± 13.18	2.18	8.6	< 0.001
PW reading fluency (3DM)	27.2 ± 8.27	43.2 ± 6.11	2.21	8.7	< 0.001
1-min TIL (max. = 36)	11.3 ± 2.88	16.3 ± 2.98	1.70	6.7	< 0.001
Phonological processing					
Phoneme deletion (max. = 18)	14.0 ± 3.21	17.2 ± 1.18	1.32	5.2	< 0.001
Spoonerism (max. = 38)	24.7 ± 10.74	33.1 ± 4.89	1.01	4.0	< 0.001
VSTM	8.2 ± 2.31	9.6 ± 2.08	0.62	2.4	0.018
RAN alphanumeric (items/sec)	2.1 ± 0.47	2.9 ± 0.41	1.76	6.9	< 0.001
Working memory					
Verbal working memory	5.8 ± 1.73	7.2 ± 1.97	0.75	3.0	0.005
Visuospatial working memory	11.9 ± 2.84	11.0 ± 2.36	− 0.33	− 1.3	0.194
Visual attention span (max. = 100)	24.3 ± 20.12	47.7 ± 30.09	0.92	3.6	< 0.001
General cognition					
Nonverbal reasoning–BD	11.6 ± 3.26	10.4 ± 2.67	− 0.40	− 1.6	0.120
Nonverbal reasoning–MAT	11.6 ± 1.96	11.0 ± 1.88	− 0.35	− 1.4	0.169
Nonverbal reasoning–PC	10.3 ± 2.36	8.9 ± 2.43	− 0.58	− 2.2	0.026
Processing speed–CODE	11.4 ± 2.93	11.9 ± 3.12	0.19	0.8	0.453
Vocabulary	10.5 ± 2.23	11.7 ± 2.07	0.54	2.1	0.038

ARQH Adult Reading History Questionnaire (higher scores indicate an increased risk of reading difficulties), *PW* pseudowords, *RAN* rapid automatized naming (alphanumeric); *VSTM* verbal short-term memory (direct digit span); *BD* block design, *MAT* matrix reasoning, *PC* picture completion, *CODE* coding

reading and phonological processing measures. Thus, six variables were used to identify clusters: word reading fluency, phonological decoding fluency (based on pseudoword reading), phoneme deletion, spoonerism, alphanumeric RAN, and verbal short-term memory. As illustrated in the dendrogram depicted in Fig. 1, the hierarchical cluster analysis resulted in two well-separated clusters. The stability of the two-cluster solution was confirmed through resampling: this solution overlapped satisfactorily with cluster solutions obtained from 1000 bootstrap samples (the average Jaccard coefficients were 0.80 and 0.72 for Cluster 1 and 2, respectively, suggesting that the obtained cluster solution is still stable even when the data set is changed in a non-essential way; Hennig, 2007).

Cluster 1 contains 20 dyslexic participants (64.5%), and Cluster 2 contains the remaining 11 participants (35.5%). Considering sociodemographic characteristics, a preponderance of women was observed in the first cluster ($X^2(1) = 3.9$, $p = 0.049$; Cluster 1: 80% females vs. Cluster 2: 46%). Clusters are similar in terms of age (Mann–Whitney U = 73.0, $p = 0.133$) and the number of school years (Mann–Whitney U = 91.0, $p = 0.451$). Participants from Cluster 1 self-reported significantly more difficulties in the Adult Reading History Questionnaire, ARHQ (M-W U = 57.5, $p = 0.029$, A = 0.74).

As expected, since clusters' identification was based on reading fluency and reading-related measures (phonological processing), between-cluster differences were strong and highly significant for most of

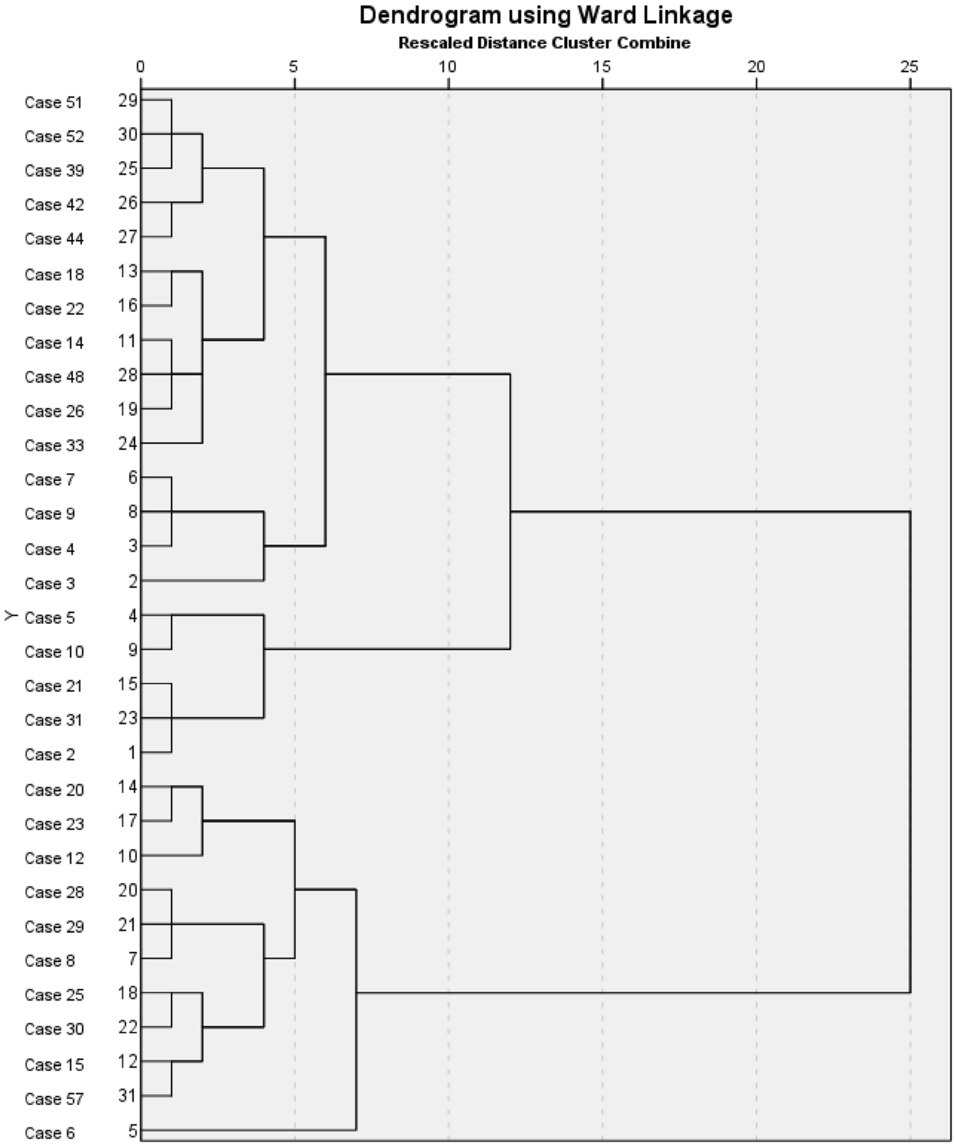

Fig. 1 Dendrogram based on Ward's algorithm illustrating the two clusters solution for the sample of 31 Portuguese adults with dyslexia

these measures: participants from Cluster 1 performed significantly below the participants from Cluster 2 on word reading fluency (M-W U = 17, $p < 0.001$, A = 0.93), phonological decoding (as measured by pseudoword reading; M-W U = 24.5, $p < 0.001$, A = 0.89), alphanumeric rapid automatized naming (M-W U = 38.5, $p = 0.002$, A = 0.83), spoonerism (M-W U = 48.0, $p = 0.009$, A = 0.78) and verbal short-term memory (M-W U = 22.0, $p < 0.001$, A = 0.90). The same happened for phoneme deletion, although the difference was moderate and not statistically reliable (M-W U = 71.5, $p = 0.113$, A = 0.68).

Regarding the other measures that were not used to define clusters, a similar pattern was observed: Cluster 1 showed a clear lower performance on reading comprehension (as measured by 1 min TIL; M-W U = 35.5, $p = 0.001$, A = 0.84) and working memory span, both in the visuospatial (M-W U = 45.0, $p = 0.006$, A = 0.80) and verbal domain (M-W U = 30.5, $p < 0.001$, A = 0.86). Although the same occurred for the visual attention span, differences were not statistically significant for this task (M-W U = 87.0, p = 0.359, A = 0.60). Differences in nonverbal reasoning tasks were also non-significant (Block Design: M-W U = 64.5, p = 0.060, A = 0.71; Matrix Reasoning: M-W U = 68.0, p = 0.087, A = 0.69; Picture Completion: M-W U = 68.0, p = 0.087, A = 0.69); however, since they always favor Cluster 2, the Nonverbal IQ index (M-W U = 43.5, p = 0.005, A = 0.80) was reliably lower for Cluster 1 compared to Cluster 2. Speed of processing was slower for Cluster 1 when compared to Cluster 2, although only marginally significant (measured by the Code subtest: M-W U = 63.5, p = 0.054, A = 0.71). Finally, vocabulary scores were also lower for Cluster 1 (M-W U = 50.5, p = 0.012, A = 0.77).

The comparisons between the two identified dyslexic clusters and the control group are displayed in Table 2 (Kruskal–Wallis' test, with post hoc comparisons adjusted by Bonferroni correction). As previously described, these results confirmed that average performance levels for Cluster 1 were systematically below those of Cluster 2, although not always identified as significant by the post hoc comparison procedure (namely, for phoneme deletion, visual attention span, and WAIS subtests).Cluster 2's performance falls in between Cluster 1 and typical readers' groups in reading measures (word reading fluency, phonological decoding, reading comprehension). However, Cluster 2 cannot be distinguished from the typical readers' group in the phonological processing measures (phoneme deletion, spoonerism, verbal short-term memory, alphanumeric RAN) as well as in visual attention span, verbal working memory, and vocabulary. Cluster 2 showed an even higher performance than typical readers for visuospatial working memory, nonverbal reasoning tasks (albeit only significant for the Picture Completion task), and Performance IQ.

Discussion

This study aimed to explore the cognitive heterogeneity of a sample of university students with developmental dyslexia in a semi-transparent orthography (European Portuguese), looking for reliable distinct subtypes based on reading and reading-related measures that have been considered the kernel of dyslexia deficits even in the adult population.

Overall, when compared to an age-matched group of typical readers, university students with a childhood dyslexia diagnosis underperformed in all literacy (-related) measures, indicating that their impairments endure in the long term. As dyslexic university students were massively exposed to written material, it is unlikely that these impairments are exclusively due to reduced exposure to print (for an insightful discussion about this topic, see Huettig et al., 2018; Vágvölgyi et al., 2021).

Consistent with prior evidence in languages varying in orthographic transparency (e.g., Elbro et al., 1994; Miller-Shaul, 2005; Pennington et al., 1990), performance deficits exhibited by our Portuguese adult dyslexic readers were stronger (Cohen's $d > 1.7$) for reading fluency measures, both in isolated word reading and reading comprehension (1-min TIL), as well as for other speed measures such as phonological decoding fluency (pseudoword reading) and alphanumeric RAN. Dyslexics' impairments were comparatively less evident for phonological short-term memory, verbal working memory, and visual attention span ($d < 1$), and for phoneme awareness measures ($d < 1.3$), albeit still large. In the current study, dyslexic adult readers also tended to present worse expressive vocabulary than typical readers, but the difference between the two reading groups was smaller ($d \sim 0.5$) and is probably a consequence of reading level (Simmons & Singleton, 2000; Vellutino et al., 2004). Thus, our results confirm recent meta-analytic findings (Reis et al., 2020) indicating that, in adulthood, dyslexia symptoms are more severe for reading and writing than for measures tapping into the cognitive processes underlying these skills (including phonological awareness and phonological memory), being exacerbated when speed, beyond accuracy, is also demanded. However, almost one-third of our participants diagnosed with dyslexia reached normative levels on the reading comprehension test (z-scores for the 1-min TIL > -1), implying that this reading skill is less impaired in adulthood for some participants, as suggested by previous studies (Beidas et al., 2013; Miller-Shaul, 2005; Parrila et al., 2007).

The agglomerative hierarchical cluster analysis of participants with dyslexia revealed two clusters (n = 20 and n = 11) that did not differ in age and number of school years and may be considered *"level*

Table 2 Descriptive for age, school years, literacy, reading, reading-related and cognitive measures for Cluster 1 and Cluster 2 and Typical readers

	Cluster 1 (n = 20) M ± SD	Cluster 2 (n = 11) M ± SD	Typical readers (n = 31) M ± SD	Eta^{2}	K-W test *p*
Age	23.4 ± 4.8	26.6 ± 8.0	25.3 ± 5.4	0.04	0.181
School years	14.6 ± 1.2	15.4 ± 1.9	14.9 ± 0.9	0.04	0.451
ARHQ	63.9^{c} ± 12.6	56.8^{b} ± 5.3	26.6^{a} ± 8.6	0.78	< 0.001
Nonverbal IQ	102.5^{a} ± 10.3	116.2^{b} ± 12.2	102.7^{a} ± 9.8	0.21	0.005
Reading					
Word reading fluency (3DM)	68.6^{a} ± 16.6	91.1^{b} ± 14.2	112.3^{c} ± 13.2	0.65	< 0.001
PW reading fluency	23.4^{a} ± 6.7	33.9^{b} ± 6.5	43.2^{c} ± 6.1	0.67	< 0.001
1-min TIL (max. = 36)	10.2^{a} ± 2.8	13.2^{b} ± 1.8	16.3^{c} ± 3.0	0.50	< 0.001
Phonological processing					
Phoneme del. (max. = 18)	13.4^{a} ± 3.2	15.2^{ab} ± 3.1	17.2^{b} ± 1.2	0.36	< 0.001
Spoonerism (max. = 38)	21.3^{a} ± 11.0	30.8^{b} ± 7.1	33.1^{b} ± 4.9	0.33	< 0.001
VSTM	7.1^{a} ± 1.7	10.3^{b} ± 1.8	9.6^{b} ± 2.1	0.32	< 0.001
RAN alphanum. (items/sec)	1.9^{a} ± 0.3	2.5^{b} ± 0.5	2.9^{b} ± 0.4	0.56	< 0.001
Working memory					
Verbal WM	5.0^{a} ± 1.7	7.1^{b} ± 0.8	7.2^{b} ± 2.0	0.25	< 0.001
Visuospatial WM	10.9^{a} ± 2.8	13.7^{b} ± 1.9	11.0^{a} ± 2.4	0.16	0.006
Visual attention span	21.2^{a} ± 16.6	30.6^{ab} ± 25.7	47.7^{b} ± 30.1	0.19	0.007
General cognition					
Nonverbal reasoning–BD	10.6 ± 3.1	13.2 ± 3.0	10.4 ± 2.7	0.12	0.057
Nonverbal reasoning–MAT	11.2 ± 1.8	12.6 ± 2.0	11.0 ± 1.9	0.09	0.083
Nonverbal reasoning–PC	9.8^{ab} ± 2.1	11.4^{b} ± 2.5	8.9^{a} ± 2.4	0.13	0.020
Processing speed–CODE	10.2 ± 2.4	12.7 ± 3.4	11.9 ± 3.1	0.07	0.092
Vocabulary	9.8^{a} ± 2.2	11.8^{b} ± 1.7	11.7^{b} ± 2.1	0.17	0.009

Within each row, means sharing the same superscript letters (a, b, and c) are not reliably different at the 5% significance level (non-parametric post hoc comparisons corrected by Bonferroni procedure), *ARHQ* Adult Reading History Questionnaire (higher scores indicate an increased risk of reading difficulties), *PW* pseudowords, *RAN* rapid automatized naming (alphanumeric), *VSTM* verbal short-term memory, *WM* working memory, *BD* block design, *MAT* matrix reasoning, *PC* picture completion, *CODE* coding

profiles”. Indeed, Cluster 2’s participants performed higher than Cluster 1’s participants in almost all literacy and literacy-related measures: reading fluency and reading comprehension, phonological decoding, alphanumeric RAN, phoneme awareness (spoonerism, but not statistically significant in phoneme deletion), phonological short-term memory, and working memory (both verbal and visuospatial). Although favoring Cluster 2, differences in visual attention span were non-reliable. Cluster 2 also showed higher general cognitive abilities, as measured by the IQ Performance Index and vocabulary. Performance on nonverbal reasoning tasks (block design, matrix reasoning, and picture completion) as well as on processing speed (coding) favored again participants from Cluster 2, although this advantage did not reach statistical significance. Interestingly, Cluster 1 self-reported more problems in a subjective reading measure (ARHQ scores), probably because these participants were more likely to be aware of the severity of their reading difficulties.

Thus, our study identified two groups of university students with dyslexia that show clearly different levels of reading measures and other reading-related variables. Although still not reading at the normative levels, the more efficient of these groups (Cluster 2) is comparable to the control typical readers in phonological awareness (phoneme deletion and spoonerism), phonological short-term memory, alphanumeric RAN, verbal working memory, and vocabulary. Furthermore, relative to control readers, Cluster 2 even showed higher levels of general cognitive abilities (composite non-verbal IQ index and picture completion subtest) as well as visuospatial memory span.

In a previous study with Portuguese children with dyslexia in the 2nd to 5th grade (Pacheco et al., 2014), two main clusters were also found: one group underperformed on phoneme deletion and RAN, compatible with a double-deficit profile (Wolf & Bowers, 1999; Wolf et al., 2002), and the other group underperformed on phoneme deletion and digit span but not RAN. In the present study with adult university students, one group (Cluster 1) also showed a double-deficit profile, whereas the other (Cluster 2) exhibited no clear deficit across the phonological domain (phoneme awareness, RAN, and phonological short-term memory), being its performance not reliably distinguished from that of control typical readers. Although we have no information about the cognitive profile of Cluster 2's participants at the time of their diagnosis in childhood, we might speculate that this cluster would correspond to the subtype of children with deficits only in phoneme awareness and verbal memory found in the study by Pacheco et al. (2014), which in turn could have been (partially) resolved during the schooling years. The (hypothesized) attenuation of the phonological deficit seems to translate into better reading outcomes in adulthood: although still showing reading performance below the typical readers, Cluster 2 outperforms Cluster 1 in reading fluency and reading comprehension.

This result seems to support the *core-deficit view* (Stanovich & Siegel, 1994). According to this perspective, the reading level is in line with the dyslexia core deficits, i.e., higher word-reading levels are essentially the result of less severe underlying deficits in phonological processing. One possible interpretation of the results might be that adults with dyslexia from Cluster 2 have resolved their phonological constraints along the development due to extensive training and systematic exposure to reading. However, as this study is cross-sectional, we cannot exclude an alternative explanation that these individuals had a less severe phonological deficit from the start compared to those from Cluster 1.

As Cluster 2's participants outperformed Cluster 1 (and even the typical readers) on general cognitive abilities, it might also be the case that these cognitive skills associated with general intelligence (additively) worked as protective factors, helping students to strategically compensate for their reading difficulties. Such interpretation gives support to the *twice-exceptionality view* (Foley-Nicpon et al., 2011), which assumes that underlying cognitive strengths and weaknesses both influence reading performance. These apparently contradictory interpretations of our results reflect the mixed findings concerning these two views on resolving dyslexia deficits, namely the *core-deficit versus* the *twice-exceptionality view* (e.g., Catts et al., 2012; Torppa et al., 2015; van Viersen et al., 2015, 2019). For example, van Viersen and colleagues (2015) found that reading differences between a dyslexic group, a gifted-dyslexic group, and a borderline-dyslexic group (2nd to 4th grades) were mainly related to the severity of their underlying cognitive deficits. In the gifted-dyslexic group, there was no clear evidence for direct compensation of cognitive deficits driven by giftedness-related protective factors, thus supporting the *core-deficit view*. Similar results were obtained in a longitudinal study with children aged from 3 to 14 by Torppa et al. (2015), who also did not find evidence for the role of protective cognitive factors to distinguish between persistent and resolving dyslexia. More recently, van Viersen et al. (2019) did find some support for the *twice-exceptionality view* on compensation in a study with 7th and 8th graders with dyslexia. The authors reported that gifted students with resolving dyslexia, compared to a persistent dyslexia group, attenuated their phonological deficits. In addition, resolvers showed more pronounced cognitive strengths (in language-related areas), which suggested that compensatory mechanisms may have contributed to attenuating literacy difficulties. The authors conclude that *both* dyslexia-related deficits and protective factors matter in resolving difficulties in dyslexia. These mixed results, apparently congruent with the two alternative views on resolving dyslexia, may be attributed to two factors. The age at which samples are tested can be decisive given that compensatory mechanisms may likely depend on the effects of educational exposure, demands and experience, thus requiring extended time to function efficiently. The other relevant factor is the opacity of the orthography in which the child learns to read and write. When transparent, orthography might facilitate the partial resolution of the phonological deficit, possibly reducing the need for compensatory reading mechanisms. Our study, testing an adult sample (who have maximum resources at their disposal), is in line with both resolving views: some adults with dyslexia were able to somewhat compensate for their reading difficulties by using other cognitive strengths, while, at the same time, aided by the semi-transparency of the European Portuguese orthography (more consistent in grapheme-to-phoneme mappings than in the reverse direction), have the severity of their dyslexia core deficits attenuated through the systematic exposure to reading and writing during school years. Nevertheless, we cannot discard other factors that might help adults with dyslexia to overcome their difficulties such as the availability and possibility to use support tools, such as voice-activated technology or audiobooks, that bolster better reading achievements (Ilaria et al., 2022).

In sum, our results indicated that the core deficits that feature dyslexia continue to be reliable in highly educated adults. In a semi-transparent orthography, a dominant and more affected subtype was linked with the lowest phonological processing skills, which may suggest that these dyslexic individuals have developmentally stable reading-related difficulties. We also found support for a dyslexia subtype characterized by superior reading outcomes along with attenuated phonological deficit and better generic cognitive factors such as nonverbal IQ, vocabulary, and (verbal and visuospatial) working memory. This more efficient cognitive profile can be considered a plausible protective factor, promoting the development of compensatory mechanisms that might have emerged after years of repeated experience with reading and allowing an ameliorated reading performance. Arguably, together with years of literacy experience, the existence of protective factors might even help some dyslexic adults who read opaque orthographies to overcome their reading impairments despite relatively weak phonological skills (e.g., Gallagher et al., 1996). More research will be needed to clarify the impact of orthography on the heterogeneity and prevalence of dyslexia subtypes. The present study added to the limited research on the expression of dyslexia subtypes in adulthood, and we encourage future studies to usefully adopt a cross-linguistic design with this sample age.

This study is not without limitations. First, it has a cross-sectional design, which ignores the dynamics of development and prevents us to clarify the origins of the heterogeneous profiles. Furthermore, given the small sample size used, the risk of underpowered statistical testing should be considered (comparing groups with 31, 20, and 11 participants provide low power to detect medium-sized effects such as Cohen's $d = 0.5$–power between 22 and 35%). Being a data-driven approach, the agglomerative hierarchical cluster analysis procedure used here is strongly influenced by the variables selected as predictors. Although the choice of the variables was based on the generic deficit profile characterizing adults with dyslexia, the inclusion of other variables (such as writing, orthographic and morphological skills) might have resulted in different subtypes. Nevertheless, these caveats do not invalidate the existence of cognitively heterogeneous subgroups of dyslexic university students, who still need to be supported to cope with dyslexia and successfully manage academic demands. Our results also suggest that one of these cognitive profiles in particular may help young adults to benefit from continued exposure to written material in a semi-transparent orthography.

The clinical approach to dyslexia has been traditionally supported by the core-deficit view, focusing on identifying the underlying deficits and remediating them with extensive training at phonological (for a review see, Galuschka et al., 2014) or word level (e.g., van Rijthoven et al., 2021). The present findings contribute to the emerging literature that argues for the role that cognitive protective factors can have in dyslexia intervention (Foley-Nicpon et al., 2011; Haft et al., 2016; van Viersen et al., 2019). Characterizing the cognitive strengths and weaknesses of students with dyslexia may be of relevance from both a clinical and educational standpoint, by allowing them to recognize their problems and provide adequate support to fulfill the reading and writing requirements in higher education, and also the opportunity to train compensatory mechanisms tailored to each specific profile.

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Data availability The data that support the findings of this study are available from the corresponding author upon request.

Declarations

Conflict of interest The authors do not have a known conflict of interest to disclose.

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