Cognitive-linguistic profiles of German adults with dyslexia

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Abstract. In the past years, educationalists and psychologists have extensively explored the reading profiles of English-speaking children with dyslexia who acquire a highly irregular and opaque orthography. Far less research has investigated reading in adults with dyslexia, especially in shallow, highly consistent orthographies like German. Addressing this gap, the current study explored cognitive-linguistic profiles of German-speaking adults with dyslexia. We provide evidence for fewer and weaker links between literacy and cognitive measures in adults with dyslexia when compared to typical readers, indicating a dissociation between cognitive and linguistic skills. Furthermore, group comparisons revealed persistent deficits in lexical access and word reading, phonological decoding and awareness, text reading comprehension, text reading speed, and spelling. In terms of cognitive abilities, only slight deficits in verbal working memory but no visuo-spatial impairments were found. In terms of language-related experiences, adults with dyslexia had considerably lower self-reported English skills and lower educational attainment. Generally, deficits in spelling, word reading, and phonological decoding were the best predictors of dyslexia, but the most widespread deficit was rapid automatized naming (i.e., speeded access to digits and letters). Our findings suggest a very heterogenous manifestation of dyslexia in German-speaking adults with low-level deficits (e.g., access to digits and letters, phonological decoding) persisting into adulthood. We thus confirm persistent phonological, reading and spelling deficits in German-speaking adults with dyslexia despite the shallow nature of the German orthographic system with highly consistent sound-letter mappings. Our findings may inform future intervention studies and help to better understand the manifestation of dyslexia across orthographic systems.

Introduction

Developmental dyslexia is a learning disorder that manifests in the form of severe deficits in reading and writing (DSM–5; APA, 2013). It affects at least two to three children in every classroom (Lyon et al., 2003; Peterson & Pennington, 2012) and deficits in reading and writing often co-occur with related cognitive deficits (Hadzibeganovic et al., 2010; Lallier et al., 2013; Peyrin et al., 2012). These comprise weaknesses in phonological awareness, lexical access, executive functioning (e.g., working memory/ WM), attention, and auditory and visual perception (e.g. Chase & Stein, 2003; Denckla & Rudel, 1976; Judge et al., 2007; Landerl et al., 2004; Pickering, 2006; Rack et al., 1992; Swanson, 1999; Vellutino et al., 2004). Deficits persist into adulthood and frequently result in lower levels of mental well-being, suggesting that while individuals with dyslexia often meet external markers of success, they may suffer higher personal and psychological strain when doing so (Wissel et al., 2021).

Most research in the field of dyslexia has been performed with speakers of English and the focus has been mainly on children. As such, conclusions on the nature of dyslexia are largely based on its manifestation within English and in children during early and later stages of literacy acquisition. Although cognitive and pre-literacy skills are largely similar across languages (Moll et al., 2014), variations in the writing system are known to affect literacy acquisition. Overall, alphabetic orthographies can be categorised on a scale from shallow to deep consistency based on their syllabic complexity and the nature of orthographic (i.e., sound to letter) mappings (Seymour et al., 2003). Whereas German and English are both alphabetic languages with a similar orthographic system and phonology, they have distinct orthographic consistencies (Ziegler et al., 2000). English, with its irregular and inconsistent grapheme-phoneme correspondences, is commonly known as having a deep orthography (Seymour et al., 2003). For instance, the pronunciation of the vowel combination ‘ou’ follows no specific rule: [aʊ] in ‘loud’, [oʊ] in ‘soul’, [uː] in ‘soup’, [ʌ] in ‘touch’, [ʊ] in ‘would’, [ɔː] in ‘four’, [ɜː] in ‘journal’, [ɒ] in ‘rough’, and [ə] in adjective endings ‘-ous’ (‘glamorous’, ‘famous’). German, in contrast, has a rather shallow orthography with highly consistent letter-phoneme combinations and few exceptions (Kessler & Treiman, 2015). As such, most letters are assigned to single sounds and exceptions usually follow simple rules. A good example for such an exception is the reduction of the letter ‘e’ in a non-accentuated syllable at the end of a word: [e] always becomes [ə] (so-called schwa), e.g., ‘viele’ [ˈfiːlə], ‘andere’ [ˈandəʁə]. Consequently, English and German differ in the extent to which the spelling of a word can be used to predict its pronunciation.

In the past few years, more and more studies have started to address the issue of orthographic depth and potential deficits in literacy and cognitive abilities in shallow languages. Recently, a meta-analysis (Reis et al., 2020) and a meta-analytic study (Carioti et al., 2021) explored the effects of orthographic depth on reading and spelling skills of individuals with dyslexia. Reis et al. explored reading skills in adults with dyslexia across alphabetic languages (N=178), focussing on (1) reading and writing, (2) reading- and writing-related skills (e.g. phonological awareness, rapid automatized naming (RAN)), and (3) cognition. They found that deficits in reading accuracy, word and nonword reading, spelling and phonological awareness were less pronounced in more shallow languages, suggesting a crucial moderating role of orthographic depth on dyslexia profiles and outcomes in adulthood (see also Swanson & Hsieh, 2009). Carioti et al. (2021) reviewed 113 studies and added age and orthographies as moderators to analyses, uncovering an age-by-orthography interaction on word reading accuracy but no effect of orthographic depth on fluency parameters. While these two works have some shortcomings, e.g., the coding of orthographic depth, subsuming children and adults and the inclusion of non-alphabetic languages (e.g., Hebrew), they point towards the orthographic depth of a language playing a significant role on dyslexia symptoms.

Regarding cognitive and reading profiles in adults with dyslexia, research suggests that primarily deficits in reading speed and writing persist into adulthood (Habib, 2000; Hatcher et al., 2002; Pammer, 2014). Highly educated adults with dyslexia have been shown to develop successful coping strategies (e.g. Pedersen et al., 2016), suggesting that educational attainment may influence the occurrence or severity of reading- and writing-related weaknesses in adults with dyslexia. Although most evidence comes again from studies with English speakers, a few studies explored cognitive-linguistic profiles of adults with dyslexia in other languages. Reid et al. (2006) uncovered that most Polish individuals with dyslexia exhibited a phonological deficit, and a small subset had a cerebellar or visual magnocellular deficit. Nergard-Nilssen & Hulme (2014) found that spelling problems were the most persistent deficit in Norwegian adults with dyslexia, with weaknesses in phoneme awareness, RAN and WM showing strong links to literacy problems. A similar pattern emerged for Dutch adults with dyslexia, where most participants shared a phonological core deficit, but large variability was uncovered in orthographic coding (i.e., accessing a printed word from memory) (Bekebredet et al., 2009). Interestingly, although German is usually named as example for a shallow orthographic system, no behavioural studies have investigated cognitive-linguistic profiles in German-speaking adults with dyslexia to our knowledge. Various studies with German-speaking children with dyslexia (Landerl et al., 1997; Ziegler et al., 2003; Landerl et al. 2013) suggest that German, in contrast to English-speaking, children with dyslexia are less accurate and slower during pseudoword and low-frequency word reading, with phonological awareness and RAN being the best predictors of phonological deficits. However, this has to be yet confirmed in adults.

To summarize, the cognitive-linguistic profiles of adults with dyslexia have been neglected in dyslexia research to date and most research was performed with English-speaking populations. Owing to this gap, it remains unclear whether and to what extent dyslexia affects reading and writing and associated cognitive abilities in varying degrees in adulthood in German speakers. Based on previous works comparing deep and shallow languages, we hypothesized that German-speaking adults with dyslexia have marginal problems with phonological decoding and awareness due to the consistent and regular sound-letter mappings in German. In comparison to typical readers, they should thus show little to no weaknesses in low-level reading skills (e.g., access to letters, digits or phonological awareness) but rather in high-level reading and writing, including word and text reading speed. In an explorative fashion, we investigated deficit profiles to uncover a potential persistent phonological deficit and the occurrence of cognitive weaknesses, such as verbal and visuo-spatial WM deficits. Additionally, we aimed to uncover the best predictors of dyslexia status, which we hypothesized to differ substantially from children, who display primarily deficits in phonological awareness and RAN.

Methods

Subjects

We tested a group of 33 young healthy German-speaking adults (control group/ CG, 16 males/ 17 females; age range: 21-39 y, M_{age} = 28.4 ± 5.0 y) and 33 young German-speaking adults with dyslexia (13 males/ 20 females; age range: 18-39 y, M_{age} = 25.6 ± 5.8 y). All participants with dyslexia were either officially diagnosed with dyslexia as a child or had exhibited literacy problems over the years with a present performance at least one standard deviation below the mean of at least 50% of administered reading and spelling tests. No subjects had any known comorbidities with other learning disorders. All participants had nonverbal intelligence scores within the normal range or above (nonverbal IQ: ≥ 91; CFT 20-R; Weiß, 2019).

Power analysis

Please note that the present sample is an extended sample from two previously published neurostimulation studies with typical adult readers and adults with dyslexia (Turker et al., 2023; Turker et al. OSF preprint). Therefore, the sample size was initially determined based on comparable previous neurostimulation studies and no initial power-analysis was performed. However, to confirm that the chosen sample size was sensitive enough to detect the expected effect sizes, we computed a post-hoc sensitivity analysis. G-power was used to perform a sensitivity calculation. Assuming α = 0.05, we had 80% power to large detect effect sizes larger than 0.717 (Effect size *d*) or 0.338 (Effect size *r*) for non-parametric two-tailed t-tests with the respective group sizes (N = 33 per group).

Procedure

All testing took place at the Max-Planck-Institute for Human Cognitive and Brain Science in Leipzig. Participants received monetary reward for their participation in the study. Prior to participation, written informed consent was obtained from each participant as approved by the local ethics committee of the University of Leipzig under the guidelines of the Declaration of Helsinki.

Reading and spelling assessment

Two separate reading abilities were assessed: the one-minute *Salzburger Lese- und Rechtschreibtest II (*SLRT-II; Moll & Landerl, 2014), testing reading speed and accuracy of both word and pseudowords. Next, the ability to read text silently was tested using the

Lesegeschwindigkeits- und Verständnistest für die Klassen 5-12+ (LGVT 5–12+; Schneider et al., 2017). Subjects were given six minutes to read a text with missing blanks which had to be filled by selecting from three options based on context. Standardised scores were calculated for reading speed (number of words read), reading accuracy (ratio of filled gaps and correct items) and reading comprehension scores (number of correctly inserted words). For spelling assessment, participants completed the *Rechtschreibungstest* (RT; Kersting & Althoff, 2003) by filling in the missing words in a German written text that was read aloud to them. The number of incorrectly written words was summarized and converted into percentages, reflecting participants' ability to spell.

Subjects performed the spoonerism task (German adaption of Perin, 1983), assessing phonological awareness. Participants were asked to exchange the first sounds of the first name and the surname of 12 well-known German personalities and characters. The inner, silent processing time and the time needed to say the correct words out loud were determined and labelled as reaction time (RT) and production time (PT).

RAN was assessed by the *Rapid Automatized Naming Test* (Mayer, 2016). Participants had to correctly name sets of colours, digits and letters as quickly as possible, and the raw score was computed by calculating the number of items named per second.

Cognitive assessment

The short form of the *Culture Fair Test Scale 2 Revision* (CFT 20-R; Weiß, 2019) was used to assess nonverbal intelligence (henceforth IQ). This standardised test contains four subtests (continuation of series, classification, matrices and topological conclusions) that have to be completed with time limits (3 vs. 4 minutes). During the short training phase, subjects received general instructions on the specific task of the subtest and had the chance to ask questions. Raw scores were transformed into age standards.

Subjects performed three verbal, phonological WM tests, namely digit span forward, digit span backward and nonword span. The stimuli for both digit span tests were taken from the *Wechsler Adult Intelligence Scale* (WAIS-IV; Petermann & Petermann, 2011). Participants had two trials to accurately repeat the digits before another element was introduced. They received one point for each correct repetition of strings, with a maximum of 14 points attainable in each task. For nonword span, the *Mottier Test* was used (Mottier, 1951), where blocks of nonword syllables had to be repeated. The test was terminated when subjects could repeat <50% of the nonword syllables. All three measures formed the composite variable verbal WM (VWM) for the discriminant analysis due to Cronbach's alpha confirming high reliability among them ($\alpha = .84$).

To assess visual-spatial WM, participants completed a computer-based version of the *Corsi Block-Tapping Test* (Corsi, 1972) for both correct order (forward condition) and reverse order (backward condition). Subjects always had two attempts to click the specific number of blocks in either forward or backward order.

Foreign language learning

Subjects were required to fill out a registration form for the participant database of the Max Planck Institute for Human Cognitive and Brain Sciences, indicating their self-rated foreign language proficiency in English (their second language) on a five-point Likert-scale, ranging from (1) very good in spoken and written language to (5) beginner's knowledge. All subjects had learnt English as their second language from age 8 on at the respective schools.

Analyses

All statistical calculations were performed with JASP 0.17.3 (Team JASP, 2023) and SPSS 27. First, Bayesian correlations were computed in JASP 0.17.3 for each group separately to explore links between reading and cognitive abilities in the two groups (typical readers vs. adults with dyslexia). We only report robust findings with a Bayesian factor (BF_{10}) > 10, which signifies robust correlations (Lee & Wagenmakers, 2014).

Following correlational analyses, group differences in behavioural performance between typical readers and adults with dyslexia were assessed using non-parametric Mann-Whitney U test as most scores in the dyslexia group were not normally distributed as assessed through the Shapiro-Wilk test in JASP 0.17.3. Please note that JASP provides the Mann-Whitney U-statistic as W since it is an adaptation of Wilcoxon's signed-rank test (Goss-Sampson, 2019). As a measure of effect sizes, the rank biserial correlation coefficient r is provided. Similar to Person's r, effect sizes of $r > 0.3$ are considered as large effects (Gignac & Szodorai, 2016; Goss-Sampson, 2019). We adjusted p-values for multiple comparisons using Holm correction with the p-adjust function in RStudio version 4.3.1 (R Core Team, 2022).

To explore the factors that could best distinguish typical readers from adults with dyslexia, we carried out a discriminant analysis including all administered reading, spelling and cognitive tests (word reading, nonword reading, spelling, digit span forward, digit span backward, nonword span, text reading comprehension, text reading speed, Corsi forward, Corsi backward, RAN digits, RAN letters, RAN colours) in SPSS 27. Combined structural matrices were computed and correlations with the respective discriminant functions below $r = .3$ were not taken into consideration.

Finally, to further investigate corresponding cognitive-linguistic profiles, different types of deficits across the dyslexia group were analysed. For this, findings from the correlational analyses, as well as Cronbach's alpha, were used to calculate composite scores for verbal WM, visual WM and RAN. Subjects were classified as impaired in the respective area if a cut-off criterion of -1.5 *SDs* below the mean of the typical readers was achieved. The significance level was set at $p < .05$.

Results

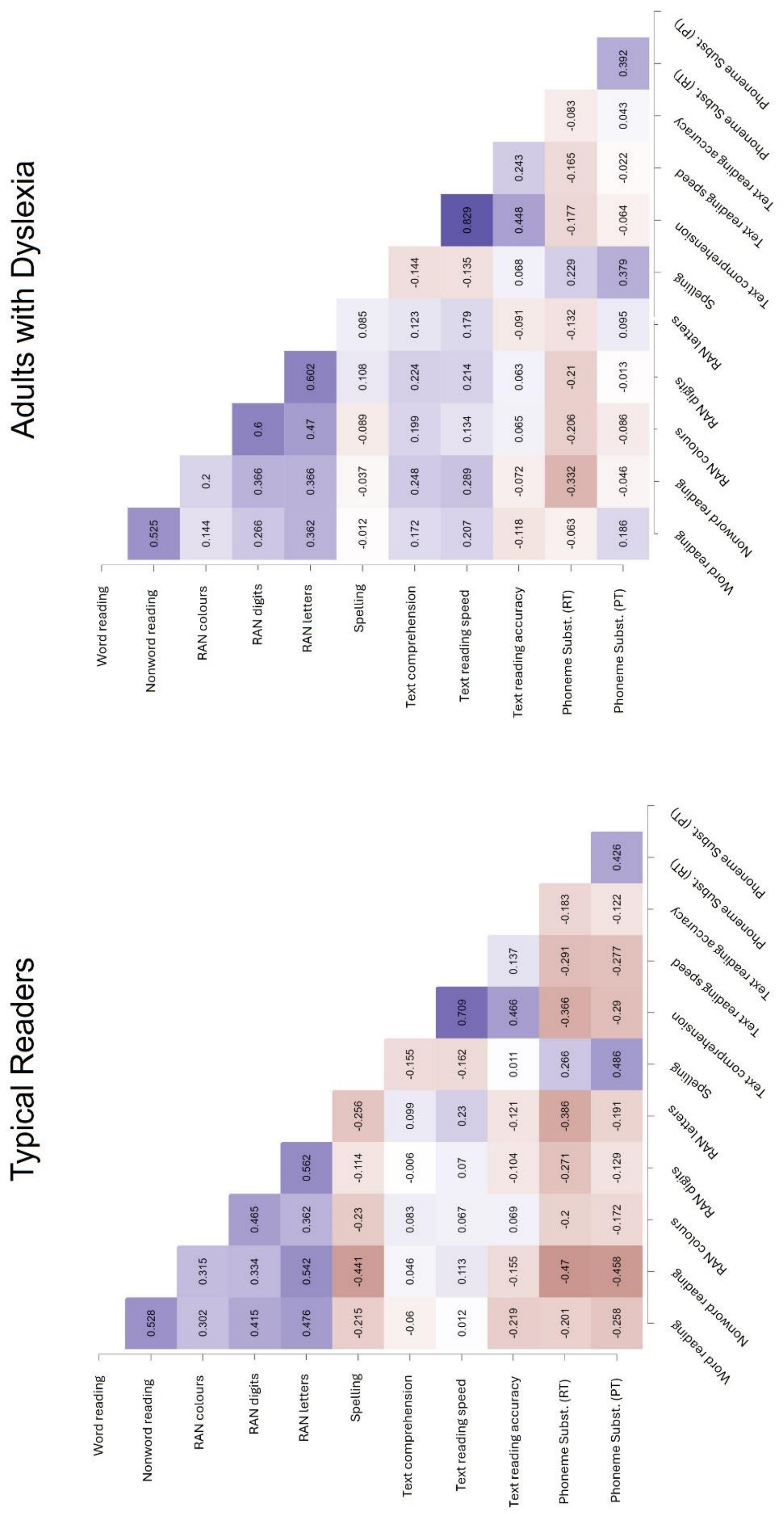
First, we investigated the link between reading(-related) and cognitive measures in typical readers and adults with dyslexia. In a next step, we compared the two groups to explore which specific abilities would show significant differences in our adult sample. Consequently, we elucidated which ability was the best predictor of dyslexia status and explored deficit profiles based on earlier accounts reporting deficits in RAN, phonological awareness and cognitive skills (verbal and visuo-spatial WM).

Correlational analyses

Overall, typical readers and adults with dyslexia showed very similar patterns of correlations, especially between literacy measures. However, these were always weaker in the dyslexia group, who showed overall less consistency in ability profiles in terms of literacy and cognitive abilities. As displayed in **Figure 1** (left side), typical readers showed strong links between different literacy measures, especially between word reading, nonword reading and RAN. Word reading was not only linked to nonword reading ($\tau = .528$, $BF_{10} = 1312.8$) but also to RAN digits ($\tau = .415$, $BF_{10} = 58.7$) and RAN letters ($\tau = .476$, $BF_{10} = 336.6$). Thus, better lexical access as measured by RAN tasks showed strong links to speeded lexical access. Nonword reading, in contrast, was linked to RAN letters ($\tau = .542$, $BF_{10} = 2096.7$), reaction times for phoneme substitution ($\tau = -.470$, $BF_{10} = 56.7$) and production times for phoneme substitution ($\tau = -.458$, $BF_{10} = 42.8$). In other words, better and faster phonological decoding, as measured through speeded nonword reading, was linked to faster phoneme substitution. Last, also naming letters (RAN letters) was positively linked to faster phoneme substitution ($\tau = -.386$, $BF_{10} = 11.2$).

In terms of cognitive skills in typical readers, verbal WM measures showed robust correlations with one another: digit span forward was linked to digit span backward ($\tau = .553$, $BF_{10} = 1580.4$) and nonword span ($\tau = .612$, $BF_{10} = 11276.3$). However, the three verbal WM measures were not linked to any literacy measure. High consistency was found for RAN performance, with RAN colour showing significant correlations with RAN digits ($\tau = .465$, $BF_{10} = 238.3$) and RAN letters ($\tau = .362$, $BF_{10} = 15.4$), as well as RAN digits with RAN letters ($\tau = .562$, $BF_{10} = 5782.7$). Furthermore, Corsi forward and backward span ($\tau = .442$, $BF_{10} = 54.2$) and phoneme substitution reaction time and production time were linked ($\tau = .426$, $BF_{10} = 25.6$). The number of languages, the level of English and the educational attainment were not linked to any reading or cognitive measure.

Figure 1. Correlations between literacy measures in typical adult readers and adults with dyslexia. Correlations are presented in Kendall's τ values with blue squares confirming a positive and red squares a negative relationship. Additionally, the darker a blue or red square, the stronger the positive or negative link.

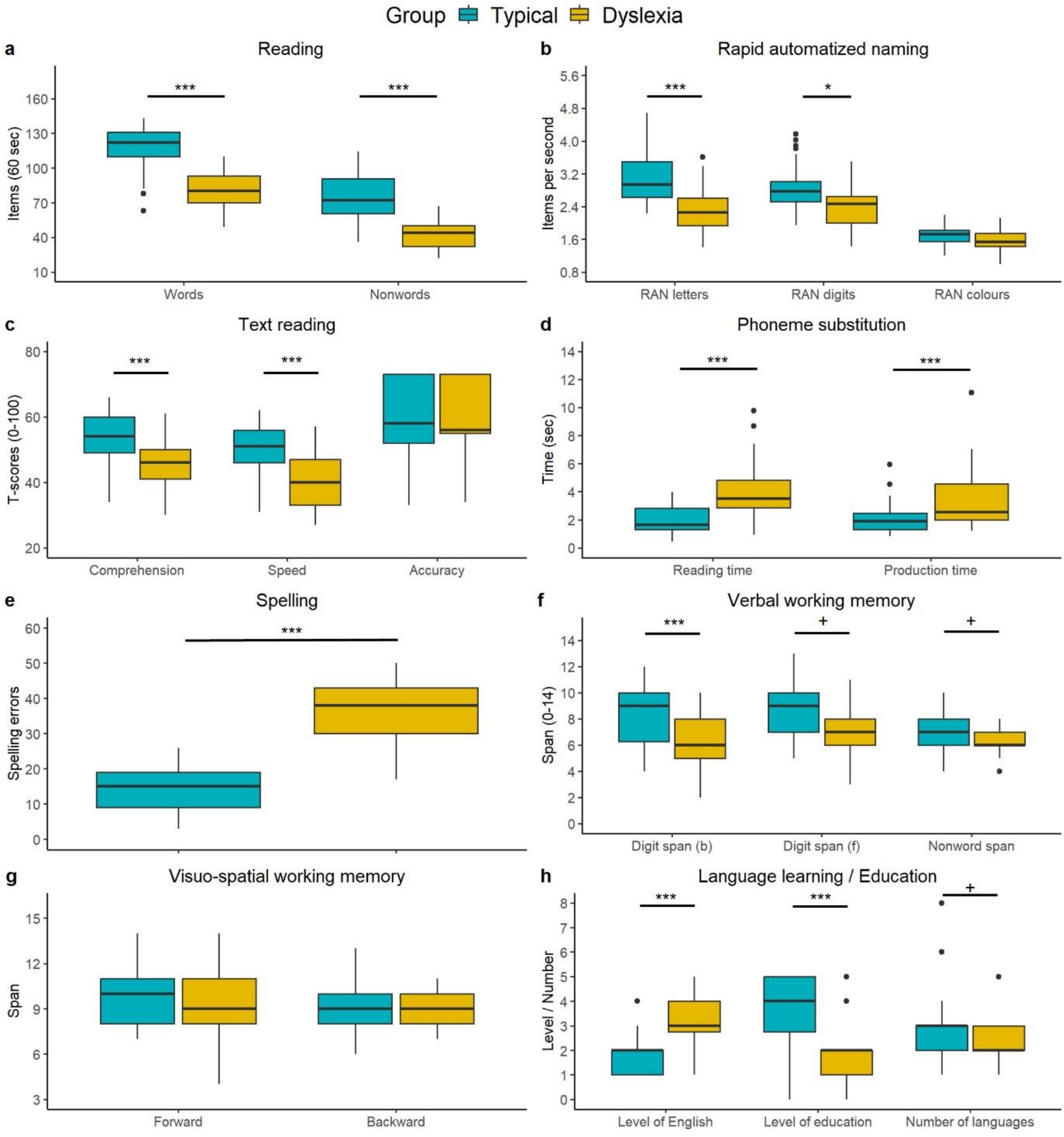


The dyslexia group, in contrast, showed overall much weaker and fewer correlations across literacy measures but strong links between similar assessments and within constructs. Correlations were found between speeded word and nonword reading (τ = .525, BF_{10} = 1592.8) and between RAN measures: RAN colour -RAN digits (τ = .600, BF_{10} = 24345), RAN colour - RAN letters (τ = .470, BF_{10} = 281.9), RAN digits - RAN letters (τ = .602, BF_{10} = 26198.8). Apart from that, text reading speed and text reading comprehension (τ = .829, BF_{10} = 7.2×10^8), Corsi span forward and backward (τ = .437, BF_{10} = 105.5) and reaction and production times for the phoneme substitution task correlated with each other (τ = .392, BF_{10} = 23.4). In terms of linguistic experience, skills and education, higher verbal WM (digit span forward) was linked to learning more foreign languages (τ = .398, BF_{10} = 16.9). Considering the link between reading and cognitive skills in dyslexia, word reading was linked to RAN letters (τ = .362, BF_{10} = 15.4), and nonword reading was linked to RAN digits (τ = .366, BF_{10} = 17) and RAN letters (τ = .366, BF_{10} = 17). Phoneme substitution correlated with verbal WM, namely digit span forward (reaction times: τ = -.367, BF_{10} = 13.4; production times: (τ = -.374, BF_{10} = 15.5). To conclude, RAN and single element reading were linked, as well as phonological awareness and verbal WM.

Group comparisons

The direct comparison between groups revealed that typical readers outperformed adults with dyslexia on almost all literacy measures. Significant differences were found for word reading (W = 1013.5, p < .001), nonword reading (W = 967.5, p = <.001), RAN digits (W = 797.5, p <.001), RAN letters (W = 906, p <.001), phoneme substitution reaction times (RT; W = 147.5, p = < .001) and production times (PT; W = 217, p = .002). Moreover, significant differences were found for text comprehension (W = 857, p = < .001), text reading speed (W = 909, p = < .001), digit span forward (W = 683.5, p = .006) and backward (W = 779.5, p = < .001). After correcting for multiple comparisons, the slight differences in age and nonword span did not reach significance. The results of the comparisons are summarized in **Figure 2** and **Table 1.**

Figure 2. Illustration of reading(-related), cognitive and linguistic abilities in typical adult readers (blue / typical) and adults with dyslexia (yellow / dyslexia). Comparisons for measures of word and pseudoword reading (a), RAN (b), text reading (c), phonological awareness (d), spelling (e), verbal WM (f), visuo-spatial WM (g) and language learning and education (h) are provided.



*p<.05, ***p<.001; + n.s. after Holm-correction

Table 1. A comparison of behavioural performance between adults with dyslexia (DYS) and typical readers (CG). Medians (*Mdn*) and inter-quartile-ranges (*IQR*s) for each group, as well as Wilcoxon rank sum test statistics (*W*), *p* value indicating significance and effect sizes in the form of rank-biserial correlation coefficient (*r*) are presented. Please note that according to our post-hoc sensitivity analysis, we had enough power to provide robust evidence for effect sizes $r > .338$.

Variable	Mdn_{CG} ***(IQR)***	Mdn_{DYS} ***(IQR)***	***W-value***	***p***	***r***
Age	29 (7)	24 (8)	722	.023+	.326
IQ	106 (16.5)	112 (18)	408.5	.236	-.175
Educational level	4 (2.3)	2 (1)	490	< .001***	.690
Word reading	122 (21)	80 (23)	1013.5	< .001***	.861
Nonword reading	72 (30.3)	44 (18)	967.5	< .001***	.832
Spelling	15 (10)	38 (13)	41	< .001***	-.925
RAN colours	1.7 (0.3)	1.5 (0.3)	692	.059	.271
RAN digits	2.8 (0.9)	2.3 (0.7)	797.5	.001*	.465
RAN letters	3.1 (0.6)	2.4 (0.6)	906	< .001*	.664
Phoneme substitution (RT)	1.6 (1.5)	3.5 (2.0)	147.5	< .001*	-.648
Phoneme substitution (PT)	1.9 (1.2)	2.5 (2.6)	217	.002*	-.481
Text reading comprehension	54 (11)	46 (9)	857	< .001***	.574
Text reading speed	51 (10)	40 (14)	909	< .001***	.669
Text reading accuracy	58 (21)	56 (18)	515.5	.706	-.053
Digit span (f)	9 (3)	7 (2)	683.5	.006+	.401
Digit span (b)	9 (3.8)	6 (3)	779.5	< .001***	.575
Nonword span	7 (2)	6 (1)	673.5	.048+	.276
Corsi span (f)	10 (3)	9 (3)	608	.064	.271
Corsi span (b)	9 (2)	9 (2)	493	.840	.030
Level of English	2 (1)	3 (1.3)	146	<.001***	-.664
Number of languages	3 (1)	2 (1)	575	.025+	.325

+ not significant after correction for multiple comparisons (Holm); * < .05, ** <.01, ***<.001 (after correction for multiple comparisons)

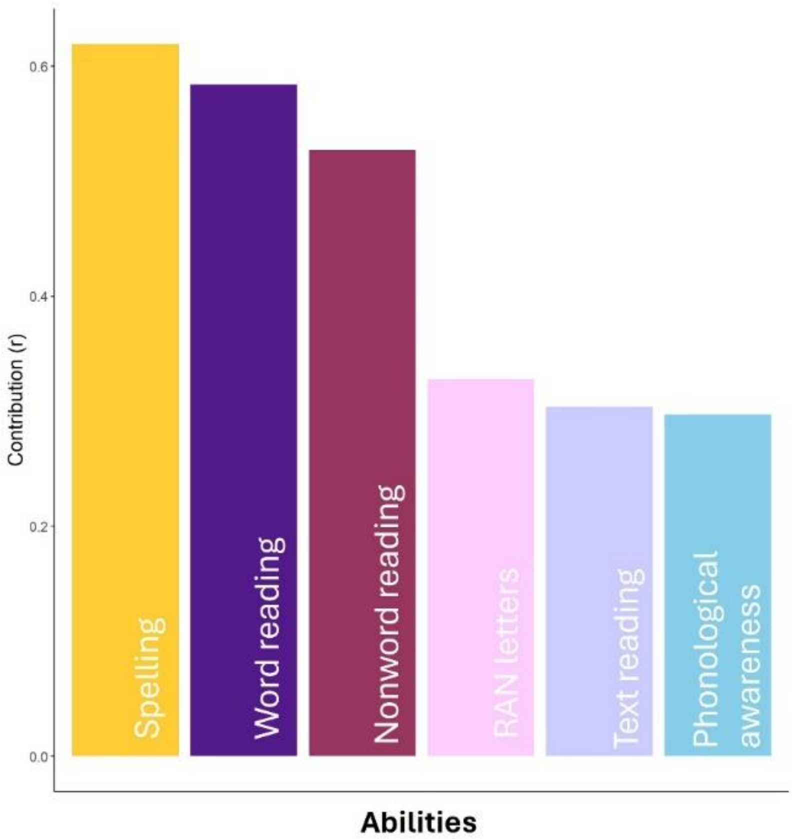
Best predictors of dyslexia

To elucidate the best predictor of dyslexia, we performed a discriminant analysis. The results of the discriminant analysis (see **Table 2** and **Figure 3**) revealed a very high classification accuracy. The assessed literacy and cognitive measures allowed for a correct classification of dyslexia status in 98.1% of cases ($\lambda = 0.197$, $\chi = 68.2$, df = 16, p = .001; 98.1% of cases correctly classified). Within the included measures, the most significant scales for group distinction were spelling ($r = .62$), word reading ($r = .58$) and nonword reading ($r = .53$). Out of the cognitive and phonological measures, only RAN letters (r =.33) showed a significant, i.e., > 0.3, contribution to the distinction between typical readers and adults with dyslexia.

Table 2. Results of the discriminant analysis indicating the contribution of literacy and cognitive variables to correctly classify adults with dyslexia ($\lambda = 0.197$, $\chi = 68.2$, df = 16, p = .001; 98.1% of cases correctly classified). Only six assessed variables significantly contributed to the correct discrimination between groups ($r > .3$, in bold, + at threshold).

Structure Matrix	
Spelling	-.619
Word reading	.584
Nonword reading	.527
RAN letters	.328
Text reading speed	.304
Phonological awareness	-.297+
Digit span backward	.250
Text comprehension	.243
Digit span forward	.225
RAN digits	.222
Phoneme substitution (PT)	-.176
Nonword span	.151
Corsi span forward	.138
RAN colours	.135
Corsi span backward	.052
Text reading accuracy	-.051

Figure 3. Visualisation of the results of the discriminant analysis, showing the contribution of all significant variables to the correct classification of participants into the dyslexia group (PA= phonological awareness).



Deficit profiles in dyslexia

In a next step, we investigated deficits in respective literacy and cognitive domains in our subjects with dyslexia. We chose a cut-off criterion of -1.5 *SDs* below the mean of the typical readers for an assessed scale to be classified as ‘deficient’. In line with previous research, we distinguished between phonological deficits (measured by phoneme substitution / PA), lexical access deficits (measured by RAN) and WM deficits.

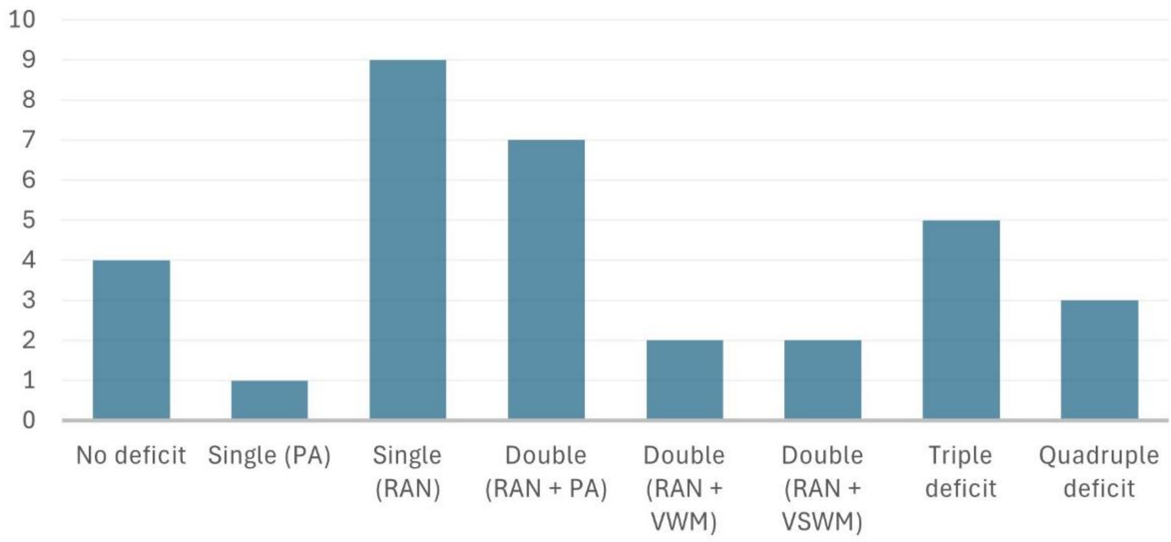
On average, most subjects with dyslexia showed severe deficits in RAN (84.9%) and phonological problems as measured by phoneme substitution (54.8%). Comparably few individuals with dyslexia had problems in verbal WM (27.3%) and even fewer in visuo-spatial WM (18.2%). Four subjects in our sample, despite having received a dyslexia diagnosis in childhood and having reported persistent reading and spelling problems into adolescence and adulthood, did not show a severe deficit in any of these reported measures. We would like to emphasize, however, that this does not necessarily mean that those subjects had performance comparable to the control group. Most likely, their performance did not meet our stringent cut-off criterion of -1.5 *SDs* below the mean.

When comparing the occurrence of deficits across subjects (**Table 3, Figure 4**), we found that roughly a third of all adults with dyslexia only had one severe deficit (30.3%). Almost all subjects in this group showed an exclusive RAN deficit. The second third (33.3%) had a double deficit, with problems in RAN and phonological processing co-occurring most frequently. Among those 15.2% of subjects that had three severe deficits, a deficit involving RAN, phonological processing and verbal WM was the most frequent. Approximately a tenth of adults with dyslexia shows severe deficits that comprise all domains, from lexical access (RAN) to phonological processing and verbal and visuo-spatial WM. Since the deficit groups were too small to run any statistical analyses (e.g., the no deficit group contained only four subjects and the quadruple deficit only three subjects), we could not run further statistical analyses comparing the groups.

Table 3. Frequency of number of deficits for PA, RAN and the two WM domains. Subtotal and total frequencies are provided. Additionally, average performances in the respective deficit groups for word reading (WR), nonword reading (NR), text comprehension (RC), text reading speed (RS) and spelling.

Cognitive-linguistic deficits	Sub-total		Total		WR	NR	RC	RS	Spelling
	N	%	*N*	%					
No Deficit			4	12.1	92.0	55.0	51.3	46.3	36.5
Single			10	30.3	81.8	44.4	44.3	38.3	36.2
PA	1	3							
RAN	9	27.3							
Double			11	33.3	78.0	41.2	47.2	39.9	32.1
RAN+PA	7	21.2							
RAN+VWM	2	6.1							
RAN+VSWM	2	6.1							
Triple			5	15.2	77.8	39.2	40.8	34.4	37.8
RAN+PA+VWM	4	12.1							
RAN+PA+VSWM	1	3							
Quadruple			3	9.1	69.0	31.7	40.3	39.0	44.7

Figure 4 Visualization of the frequency of number of deficits for PA, RAN and the two WM domains across all 33 subjects.



Discussion

The present work aimed to shed further light on the manifestation of dyslexia in German-speaking adults. So far, most research has focused on English-speaking populations and children. This is problematic since the orthographic depth of a language influences reading acquisition and the encountered deficits in dyslexia. Additionally, deficits change over time and are compensated for, potentially resulting in very different weaknesses in adults as compared to children and teenagers. The four main aims of the present work were to (1) elucidate the intricate link between cognitive and literacy abilities, (2) explore persisting weaknesses, (3) determine the strongest predictors of dyslexia status and (4) investigate deficit profiles in RAN, PA and WM as done in earlier studies. Please note that it was our assumption that dyslexia might manifest differently in German-speaking adults than in speakers of orthographically deep languages and differently than in German-speaking children. Since we did not directly compare these groups in the present work, we can only link them to what has been suggested by previous research.

Based on German being a shallow language, we hypothesized that (1) reading skills were less reliant on phonological skills (like PA) and not as dependent upon cognitive skills, and (2) German-speaking adults with dyslexia had little to no weaknesses in low-level reading skills (e.g., access to letters, digits or phonological awareness) but marked deficits in high-level reading and writing, including word and text reading speed. Simple phoneme-grapheme correspondences in shallow languages facilitate faster learning of letter-sound relationships and decoding skills. This is backed by behavioural research providing evidence for orthographic depth influencing the cognitive underpinnings of typical adult reading (Schmalz et al., 2014, Ziegler et al., 2001), the speed of literacy acquisition (Landerl, 2000, Wimmer & Goswami, 1994), the prevalence, severity and symptoms of impaired reading (e.g., dyslexia; Landerl et al., 1997) and the impact of cognition on reading ability (Caravolas et al., 2012, 2013). In terms of correlations between literary and cognitive measures, we observed few and substantially weaker links between skills in the dyslexia group as compared to a control group. Interestingly, neither cognitive, nor linguistic (number of languages, level of English) or educational (educational attainment) factors correlated with reading and spelling abilities. These rather weak links between abilities that should go hand in hand, as confirmed by the group of typical readers, could point towards a very heterogeneous manifestation of dyslexia with large differences in test performance and thus a lack of consistency. Moreover, it confirms that more phonology-related skills are not necessarily strongly tied to skills relying on lexical access. Regarding the second hypothesis, we found that German-speaking adults in their twenties and thirties still display severe deficits in various reading and cognitive measures not limited to high-level reading skills. More specifically, we suggest that long-term deficits across all reading measures extend to issues in verbal WM, lower educational attainment, and lower foreign language skills. This supports findings from deep orthographies, such as English, which revealed problems across literary and cognitive skills that persisted long into adulthood (Hatcher et al. 2002). When directly comparing the groups, we found that despite normal nonverbal intelligence (and on average even higher IQ scores than the typical readers) and the absence of other learning or developmental disabilities, German-speaking adults with dyslexia performed significantly worse on all assessed literacy measures. This included word and nonword reading, text reading comprehension and speed, spelling and measures of lexical access (RAN), as well as phonological awareness. This is also in line with studies with speakers of deep orthographies suggesting that adults with dyslexia differ from typical readers in terms of reading-related cognitive deficits (Ramus et al. 2003, Reis et al., 2020), primarily in phoneme awareness and WM performance (Swanson & Hsieh, 2009). Interestingly, most of our test instruments stemmed from diagnostic batteries to diagnose children with dyslexia since no adult versions were available. In other words, twenty to thirty years after the period at which dyslexia is usually diagnosed in Germany (~ 7 years in first grade), these tests seem to be valid instruments to confirm dyslexia status in adulthood.

As a third aim, we wanted to explore which factors best predicted dyslexia status and were keen to see whether the factors would match findings of studies with German-speaking school children. As hypothesized, the present study failed to corroborate findings of previous research in German-speaking children with dyslexia (e.g., Landerl et al., 1997; Ziegler et al., 2003; Landerl et al. 2013), where phonological awareness and RAN were the best predictors of phonological deficits in dyslexia. According to the results of our discriminant analysis, spelling was by far the strongest predictor of a history of dyslexia, and difficulties did not only persist in the pseudoword and low frequency word domain but reading speed deficits also affected simple words. While this is not in line with observations in German-speaking children, it corroborates the few existing earlier studies in adults with dyslexia reporting that spelling errors and problems with reading fluency are the most persistent characteristics of dyslexia in adulthood (Nergard-Nilssen & Hulme, 2014, Callens et al., 2014, Kemp et al., 2009). Previous studies in both deep and shallow writing systems, however, suggested that phoneme awareness, orthographic knowledge and RAN were the most important predictors of reading and spelling in adulthood (Furnes & Samuelsson, 2011). In German-speaking adults with dyslexia, RAN and phonological problems were still frequently found but they were not sufficient to correctly predict who has dyslexia and who does not. Overall, we confirm the importance of phonological processes in German-speaking adults with dyslexia, countering previous studies claiming that phoneme awareness is not important in shallow languages (Landerl & Wimmer, 2009; Mann & Wimmer, 2002). The significantly worse performance on our phoneme substitution task backs evidence on a persistent phonological deficit in dyslexia across orthographies and languages (e.g., Bekebrede et al., 2010; Reis et al., 2020).

Last, we uncovered deficit profiles in dyslexia and provided support for lexical access being the most widespread deficit in German-speaking adults with dyslexia. In the present sample, the most widely represented deficits were deficits in RAN (84.9%) and PA (54.8%). Surprisingly, not even a third of our subjects with dyslexia showed deficits in verbal WM (27.3%) and even fewer had problems with visuo-spatial WM (18.2%). This raises the question whether phonological working memory problems are really a feature of dyslexia or just found in a subgroup. Several studies and reviews confirmed verbal WM problems in German-speaking children with dyslexia, but it remains debated whether these affect only the phonological loop (Maehler & Schuchardt, 2016; Steinbrink & Klatte, 2008) or the central executive, or both (Fischbach et al., 2014; Schuchardt et al., 2013). We also provide further evidence that tasks with higher working memory demands (e.g., manipulation of input instead of just storing), digit span backward in our study, are more difficult for individuals with dyslexia than simple WM tasks, as previously found in teenagers and young adults with dyslexia (Vasic et al., 2008). The fact that very few subjects with dyslexia had visuo-spatial WM deficits adds to the existing literature, where some studies found differences in visuo-spatial WM (Fischbach et al., 2014), while others did not (Brandenburg et al., 2015). Since most studies exploring visuo-spatial WM deficits were with German-speaking children, the present study adds to a weak indication of visuo-spatial WM deficits in dyslexia, with only two out of ten adults with dyslexia displaying severe deficits in this domain. About a tenth of our dyslexia sample showed no severe cognitive deficit (12.1%), which is probably due to the stringent cut-off criterion of 1.5 *SDs*. As such, this rather reflects less severe impairments that did not meet this criterion than no literacy and cognitive impairment at all. It could, however, also support earlier findings that educated adults with dyslexia may adopt strategies to cope with the deficits (Gregg et al., 2007; Mortimore & Crozier, 2006; Pedersen et al., 2016; Ransby & Swanson, 2003). All in all, we provide strong evidence for different dyslexia subtypes, with single deficits in RAN and double deficits in RAN and PA occurring most frequently in German-speaking adults with dyslexia. Interestingly, only one subject in the present study had a single deficit in phonology (PA). Conversely, a third of our sample had a single deficit in lexical access (RAN). The extent to which this translates to findings in our whole testing battery and whether the groups differ on other cognitive and literacy measures remains to be further explored in larger samples.

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