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Visual noise effect on reading in three developmental disorders: ASD, ADHD, and DD

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Abstract

Background and aims: Developmental disorders such as Autism Spectrum Disorder (ASD), Attention Deficit Hyperactivity Disorder (ADHD), and Developmental Dyslexia (DD) are reported to have more visual problems, oral language difficulties, and diminished reading skills in addition to their different diagnostic features. Moreover, these conditions also have increased internal noise and probably an impaired ability of external noise filtering. The aim of the present study was to compare the reading performance of these groups in the presence of external visual noise which disrupts the automatic reading processes through the degradation of letters.
Methods: Sixty-four children and adolescents in four groups, ASD, ADHD, DD, and TD, participated in the study. Two types of stimuli were used – unrelated words and pseudowords. The noise was generated by exchanging a fixed number of pixels between the black symbols and the white background distorting the letters. The task of the participants was to read aloud the words or pseudowords. The reading time for a single letter string, word or pseudoword, was calculated, and the proportion of errors was assessed in order to describe the reading performance.
Results: The results obtained showed that the reading of unrelated words and pseudowords differs in the separate groups of participants and is affected differently by the added visual noise. In the no-noise condition, the group with TD had the shortest time for reading words and short pseudowords, followed by the group with ASD, while their reading of long pseudowords was slightly slower than that of the ASD group. The noise increase evoked variations in the reading of groups with ASD and ADHD, which differed from the no-noise condition and the control group with TD. The lowest proportion of errors was observed in readers with TD. The reading performance of the DD group was the worst at all noise levels, with the most prolonged reading time and the highest proportion of errors. At the highest noise level, the participants from all groups read the words and pseudowords with similar reading speed and accuracy.
Conclusions: In reading words and pseudowords, the ASD, ADHD, and DD groups show difficulties specific for each disorder revealed in a prolonged reading time and a higher proportion of errors. The dissimilarity in reading abilities of the groups with different development is most evident when the accuracy and reading speed are linked together.
Implications: The use of noise that degrades the letter structure in the present study allowed us to separate the groups with ASD, ADHD, and DD and disclose specifics in the reading process of each disorder. Error type analysis may provide a basis to improve the educational strategies by appropriately structuring the learning process of children with TD, ASD, ADHD, and DD.

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Introduction

Reading is a necessity in everyday life, essential to our participation in modern society (Chung et al., 2019). The ability to read entails transforming written symbols, the letters, into their corresponding sounds and integrating them into a single word. Many cognitive and linguistic factors are involved in the process of learning how to read. During the earlier educational stages, children examine written words by sequential decoding, in which attention to individual letter-sound associations, formed phonological awareness such as blending and segmentation, verbal working memory, and local visual analysis are specially required (Giovagnoli et al., 2016). With improving their reading skills, children start to recognize the characteristic shape of some words as a whole.

Reading disorders are most often associated with the condition of Developmental Dyslexia (DD). Children with dyslexia read words and nonwords considerably slower than children with typical development (TD, e.g., De Jong and Van der Leij, 2003; Wimmer, Hutzler & Wiener, 2002; Taroyan & Nicolson, 2009). DD is commonly described as a language-based disorder in which the phonological processing is often compromised (for a review, see Peterson & Pennington, 2015). However, reading is a complex cognitive process in which not only phonological skills but also auditory processes, memory abilities, attention processes, and visual-spatial skills are involved (Pennington, 2006; Menghini et al., 2010). Visual-spatial processes play a crucial role in reading, and several studies reported a relationship between visual-spatial deficits and DD (Talcott et al., 1998, 2000; Vidyasagar & Pammer, 2010; Stein, 2014; Gori & Facoetti, 2015). People with reading difficulties, including dyslexia, often report vision-related symptoms, and many of the reading errors have been explained as the outcome of poor visual processing (Stein & Walsh, 1997). According to Shovman and Ahissar (2006), the most significant difficulties in participants with dyslexia were in 3–4 letter words and pseudoword reading. It is possible that, they needed to gain more visual information and identify precisely each letter and could not just "scan" easily the text, as skilled readers do.

Although the reading impairment is a key feature of DD, reading difficulties may also occur with other developmental disorders (Nandakumar & Leat, 2008) such as Attention Deficits Hyperactivity Disorder (ADHD, Lobo & Lima, 2008; Sciberras et al., 2014; Tamm at al., 2014) or Autism Spectrum Disorder (ASD, Nally et al., 2018). Remarkably, these three disorders also share noise exclusion deficits (Sperling et al., 2005; 2006; Park et al., 2017) and/or probably have altered levels of neural noise. Increased neuronal variability was described in dyslexia (Hancock et al., 2017), in ASD (Milne, 2011; Dinstein et al., 2015; Haigh et al., 2015; Weinger et al., 2014), and ADHD (Gilden & Hancock, 2007; Bubl et al., 2015; Gonen-Yaacovi et al., 2016). Oral language difficulties are another feature that is common for these disorders (Botting, Bean-Ellawadi, & Williams, 2016) and could also contribute to difficulties with the written language. For instance, children with Developmental Language Disorder (DLD) often develop reading problems (Bishop et al., 2009; Erisman & Blom, 2020). As Bishop and Snowling (2004) pointed out, reading complications could be multi-causal due to the dynamic and interactive process of learning to read. Erisman and Blom (2020) summarized that various abilities play a role in reading, including oral language abilities as well as executive functions (especially working memory and interference control).

Autism is a spectrum condition characterized by deficits in communication, reciprocal social interaction, and restricted and stereotyped patterns of behaviours or interests (DSM-5, APA, 2013; ICD-10, World Health Organization, 2004). Readers with ASD generally performed within the typical levels of word and nonword reading and have average to good range for word reading accuracy, but have imperfect decoding skills and poor comprehension (e.g., Calhoon 2001; Nation et al., 2006; Baixauli et al., 2021) as well as word recognition (Gabig, 2010). May et al. (2015) found similar word reading achievement in the ASD group compared to the TD group. Gabig (2010) reported that 5–7 years old children with autism read single words or nonwords correspondingly to the age-matched TD controls. However, Nally et al. (2018) found impaired reading abilities in participants with ASD compared to the TD participants. The reading deficits were stronger in participants with more severe symptoms of autism. Åsberg and Sandberg (2010) also found a poor-readers' subgroup with severe problems in the ASD group.

ADHD is characterized by an early onset and a persistent pattern of inattention and/or hyperactivity-impulsivity that interferes with functioning or development and directly impacts on academic, occupational, or social functioning (DSM-5, APA, 2013; ICD-10, World Health Organization, 2004; ICD-11, World Health Organization, 2019). Concerning reading performance in children with ADHD, Sciberras et al. (2014) found a high prevalence of language problems in children with ADHD, which caused them to have a reduced reading speed of words. Kadesjö et al. (1999) found in a school-based study that 40% of the children with ADHD had reading problems and 29% - writing problems. Individuals with ADHD have difficulty identifying written words (McGrath et al., 2011; Willcutt et al., 2010), demonstrating slower, less accurate sight word reading and nonword decoding (Ghelani et al., 2004; Jacobson et al., 2011). Lobo and Lima (2008) found that children with ADHD made more mistakes during silent reading than the control group. Participants with ADHD had poorer performance than the control group participants and preferred using phonological processing, which characterizes the alphabetic phase of reading (Ehri, 2000).

Written words could be processed and recognized by the lexical route or by the sublexical (nonlexical) route (Coltheart et al., 1993; Coltheart et al., 2001). While the lexical route operates with word templates in the lexical memory and is important to read familiar words, the sublexical route uses grapheme-to-phoneme correspondences and helps in reading unknown words and pseudowords. Lexical reading is associated predominantly with reflexive attention, whereas sublexical reading –with voluntary attention (Ekstrand et al., 2019).

It was suggested that in phonological dyslexia, it is difficult to read uncommon words and pseudowords while in surface dyslexia, the reading difficulty is connected to the irregular words because of problems with the lexical route (e.g., Castles and Coltheart, 1993). Moreover, Gori et al. (2014) suggested that a magnocellular-dorsal deficit which is often reported in individuals with DD might impair the sub-lexical mechanisms. Regarding the reading specific features of people with ASD, it was suggested that even simple familiar words are processed through an additional activation of the sublexical route and reduced activity in the lexical route compared to the controls with TD (Moseley et al., 2014). It was assumed that people with ADHD could have deficits in both lexical and sublexical route processing (de Jong et al., 2012). Hence, we expect to observe differences in the reading performance of the distinct groups in tasks that involve different participation of the sublexical and lexical routes of processing. To test this hypothesis, we decided to include both words and pseudowords in our study.

Although ASD, ADHD, and DD refer to specific patterns of behavioural and learning difficulties with different core defining features, all three disorders share a common feature related to performance efficiency. It is limited by external noise in the sensory signals and by internal noise associated with random variations of neuronal activity. Noise is inherent to external sensory stimuli and may affect the inner noise through rising trial-to-trial variability at any stage of perception (Faisal et al., 2008). Disproportionately high levels of neuronal variability could be produced at both the single-cell level and the neural network level. The increased neuronal variability probably has a different origin in the three developmental disorders. In dyslexia, evidence of increased neuronal variability was found with auditory stimuli. Hornickel and Kraus (2013) described weaker response consistency of auditory brain stem EEG responses in poor readers compared to good readers, which was independent of resting neurophysiological noise levels. Hancock et al. (2017) formulated a neural noise hypothesis of DD, assuming that visual and auditory low-level sensory-processing deficits precede and underlie phonological problems. Sperling et al. (2005; 2006) observed that higher thresholds for poor readers than good readers were found only in conditions that included external visual noise. To explain this finding, they assumed that in addition to increased neural variability, deficits in noise exclusion ability might also be responsible for diminished performance in visual tasks.

Both the increased internal noise and the diminished external noise filtering were also described in autism. Higher neural variability was observed in individuals with ASD in the visual modality (e.g., Milne, 2011; Weinger et al., 2014) and in visual, somatosensory, and auditory modalities (Dinstein et al., 2012; Haigh et al., 2015). In addition, the ability to filter the noisy signals is reduced in people with ASD. The segregation of signal from noise is diminished across various motion processing tasks (Manning et al., 2017), and the detection of visual signals in Gaussian noise was poorer (Sanchez-Marin & Padilla-Medina, 2008). Zaidel et al. (2015) observed increased sensitivity to sensory noise in people with ASD, resulting in the greater effect of the stimulus noise added to visual motion. Park et al. (2017) found that both poorer external noise filtering and high levels of inner noise restrict visual processing in the group with ASD.

There is evidence that listening to white noise could benefit the cognitive performance of people with ADHD (e.g., Söderlund et al., 2007). White noise therapy is supposed to improve at least some tasks such as speech recognition and reading and writing speed (reviewed by Pickens et al., 2019). One hypothesis for white noise's positive effect is that individuals with ADHD have a low level of neural noise, and adding external noise aids in achieving optimal performance (Söderlund, et al., 2007). However, it is unclear what the effect of the external visual noise would be because the results of Michalek et al. (2014) showed that people with ADHD benefited less from visual information during noise than the control group. Moreover, elevated background noise is found in people with ADHD at the retinal level (Bulb et al., 2015), which would influence the processing of noisy visual stimuli.

Interestingly, in autism and dyslexia, increased inner noise was described only during sensory responses but not at a resting state. In ADHD, the larger neural response variability is not connected to a specific sensory or cognitive process but acts continuously (Gonen-Yaacovi et al., 2016). Indeed, Gonen-Yaacovi et al. (2016) found more considerable trial-by-trial EEG variability in the ADHD group than in the TD group before and after stimulus presentation (independent visual and auditory stimulations) and in trials where the stimulus was omitted. Machida, Murias, and Johnson (2019) found that the greater variability corresponded to higher levels of ADHD symptoms. An earlier study (Saville et al., 2015) observed increased neuronal variability in ADHD individuals during later decision-making processes, reflected in P300 wave.

The present work aimed to study how external visual noise influenced the ability to read in ASD, ADHD, and DD, because these developmental disorders are affected by the diminished external noise filtering and the increased internal variability. To explore the influence of low-level visual factors on reading through lexical and sublexical routes, we added visual noise to words and pseudowords at the local level of word processing which distorts the letters, thus disrupting the automatic reading processes. Such noise poses significant demands on local visual analysis and would interfere with each stage of reading, starting from the letter identification and letter combination (graphemes), their conversion to sounds (phonemes), the combination of phonemes in a word pronunciation (phonology), and the level of meaning (semantics). It could be expected that the reading performance of all participants will be impaired, however, in a different specific manner for each of the disorders. We focused our attempts on studying the initial stages of the reading process tightly connected to visual perception. Hence, the experimental design was not appropriate to investigate the reading comprehension since we used unrelated words and pseudowords to avoid the influence of semantics.

Methods

Participants

Sixty-four children and adolescents who participated in the study belonged to one of four groups, namely ASD, ADHD, DD, and TD groups. They were part of a larger, ongoing visual perception study. All groups were matched as closely as possible with regard to potentially relevant background variables.

The following general criteria for inclusion were applied: (1) age 8 to 16 years; (2) all participants had to be cooperative and able to follow instructions; (3) normal or corrected-to-normal vision; (4) the native language is Bulgarian. (5) Parents of participants were asked to complete a developmental questionnaire and had a brief clinical interview about any developmental problems or complaints about scholastic results. Additional criteria were applied for each group.

TD Group: Typically developing children/adolescents were recruited via the Regional Department of Education - Sofia city from public schools after the consultation with the school psychologist and met all of the inclusion criteria. Additionally, parents do not report information about any developmental problems or complaints about scholastic results. The exclusion criteria were as follows: Developmental disorders, for example, ASD, Intellectual disability, etc., Sensory problems, or related medical conditions.

Clinical groups: All participants from groups with ASD, ADHD, and DD were recruited via the Sofia Centre for Social Rehabilitation and Integration - autism spectrum priority, the Regional Centre for Support of the Inclusive Education Process-Sofia-city, and through community organizations, parental associations, and professionals (psychologists, speech therapists, child psychiatrists, etc.) and met all of the inclusion criteria and parents reported information about developmental problems related to ASD, ADHD, or DD for each of the groups. Additionally, all children/adolescents had an established clinical diagnosis of ASD, ADHD, or DD according to ICD-10 (World Health Organization, 2004) and met diagnostic criteria from the DSM-5. Participants from the clinical groups had to be above the cutoff scores according to the Autism Diagnostic Interview-R (ADI-R; Lord, et al., 1994, Rutter, et al. 2003, ADI-R, 2003) for ASD; Conners rating scale 3rd Edition for ADHD (Conners, 2008); Dislessia e Della Disortografia Evolutiva-2 (DDE-2; Sartori, et al., 2007) for DD. The Exclusion criteria were as follows: (1) Other developmental disorders; (2) Major medical or neurological problems; (3) Use of psychotropic medication within the last 3 months before the study started.

All participants in the experimental cohort were classified respectively as children with ASD, ADHD, and DD according to their scores from diagnostic tests and clinical consultation by an experienced clinical psychologist, a developmental psychologist (and a school psychologist for the TD group).

Wechsler Intelligence Scale for Children–Fourth Bulgarian Edition (WISC–IV BG; Wechsler, 2003) was administrated for all groups. The resulting scores in Verbal Comprehension Index (VCI), Perceptual Reasoning Index (PCI), Working Memory Index (WMI), Processing Speed Index (PSI), and Full-Scale IQ (FSIQ) are given in Table 1.

Parents of the participants signed informed written consent before the study, and the participants gave their consent orally. The authors encouraged parents and participants to read and understand the study procedures before completing the consent form, ask any questions, and ensure they are comfortable before they sign the consent form. The participation was voluntary and could be terminated at any time by the participants or their parents. The experimental procedure was in agreement with the ethical standards of the Declaration of Helsinki and its later revisions and was approved by the Ethics Committee of the Institute of Neurobiology, Bulgarian Academy of Sciences (reference EC-INB/2018.40).

Stimuli and procedure

The stimuli were presented on an EizoColorEdgeCS230 23″ monitor with a screen resolution of 1920 × 1080

Table 1. Results of Wechsler intelligence scale for children–fourth Bulgarian edition.

		Participants with TD	Participants with DD	Participants with ASD	Participants with ADHD
N (male/female)		16 (10/6)	16 (8/8)	16 (10/6)	16 (13/3)
Age Mean ± SD [range] in years		10.5 ± 1.5 [8–14]	10.6 ± 2.1 [8–16]	10.5 ± 1.7 [8–13]	10.5 ± 2.3 [7–16]
WISC-IV (Mean ± SD [range])	**VCI**	101.81 ± 7.44 [85–115]	93.43 ± 12.10 [72–113]	83.06 ± 13.43 [62–110]	108.12 ± 13.4 [87–128]
	PRI	94.00 ± 12.0 [76–114]	100.06 ± 16.45 [64–128]	96.68 ± 22.16 [58–136]	103.50 ± 16.5 [71–129]
	WMI	102.00 ± 10.77 [90–123]	89.87 ± 11.44 [74–112]	92.87 ± 15.76 [71–123]	95.93 ± 16.36 [69–133]
	PSI	93.37 ± 8.69 [78–109]	95.75 ± 12.75 [80–124]	86.18 ± 12.38 [55–102]	91.87 ± 12.53 [72–112]
	FSIQ	96.87 ± 9.11 [80–117]	93.43 ± 11.24 [71–113]	87.68 ± 13.99 [62–113]	101.06 ± 13.4 [75–124]

pixels and a vertical refresh rate of 60 Hz. The stimuli were generated by an OpenGL video card using a custom software package. The reading of participants was recorded by using a microphone.

Two types of stimuli or letter strings were used – Bulgarian words and pseudowords. The pseudowords were generated using the involved words by means of a modified version of Wuggy: a multilingual pseudoword generator (Shtereva et al., 2020; Keuleers & Brysbaert, 2010). Our study was designed to assess the role of external visual noise on reading in conditions as close as possible to everyday reading. Usually, the reading text is arranged in pages, and each page consists of many lines which involve many words. Hence, our test samples were arranged in “pages”, and fifteen lines of words or pseudowords were simultaneously displayed on the monitor screen. The target line was situated in the middle of the screen (i.e., the eighth line) and was marked by arrows from the left and the right side. The font was Courier New. The height of the letters was 0.74° from a viewing distance of 70 cm, and their contrast was 90%. The noise was generated by exchanging an appropriate number of pixels between the black letters and the white background (Figure 1). The noise level was determined by the percentage of exchanged black and white pixels. 5 noise levels were used: 0, 50, 55, 60, and 62.5%.

The generation method ensured the same average brightness of the screen, regardless of the noise level used. Words and pseudowords were presented in different blocks. In each block 3- and 7- letter words or pseudowords were used but were placed on separate pages. The active readable line contained 15 words or pseudowords in the 3-letter version or eight words or pseudowords in the 7-letter version, respectively. 30 pages were arranged for predetermined combinations of 3- or 7- letter words at the different noise levels and 30 pages – for the pseudowords. In each block all 3- and 7-letter words or pseudowords at predetermined noise levels were intermixed and presented in a pseudo-random order. The pages without noise (level 0) were presented last in the blocks.

The experiment was controlled by a personal computer using a custom software package. Initially, a noise frame corresponding to the noise level of the stimulus page was displayed on the monitor screen. An arrow fixation mark indicated the beginning of the active reading line. The participants started reading by pressing the left joystick button on a controller, thus loading the page of words or pseudowords at the predetermined noise level. Simultaneously with the appearance of the stimulus, an audio recording was started. The task of the participants was to read aloud the words or pseudowords from the active reading line. After reading the last reading item from the line, the subject pressed the right joystick button. In such a way, the audio recording was stopped, and another noise frame appeared on the screen.

The experimental procedure was explained and demonstrated to the participants who were cooperative and understood the task as proved in training trials.

Statistical analysis

To describe the reading performance, we calculated the reading time for a single letter string, word, or pseudoword, based on the total time for reading from the first to the last read letter string on a target reading line divided by the number of the letter strings read. We also determined the proportion of errors as the number of incorrectly read letter strings divided by the total number of read letter strings. All analyses were performed in the R environment (R Core Team, 2020). The protocol described in Zuur, Ieno, & Elphick (2010) was used for data exploration and selecting appropriate models.

We used a generalized linear mixed regression model to evaluate the effect of letter number, letter string type (words or pseudowords), noise level, and the group of participants on the number of errors. The package glmmTMB (Brooks et al., 2017) was applied. We tested various zero-inflation models as the preliminary data exploration suggested more zeros in certain conditions.

For testing the effect of the experimental factors on the reading time, we used a generalized mixed model regression with Gamma and inverse Gaussian distributions and identity link (as suggested by Lo & Andrews (2015) or a log link. For the distribution and link function selection, we used the lme4 package (Bates et al., 2015). To

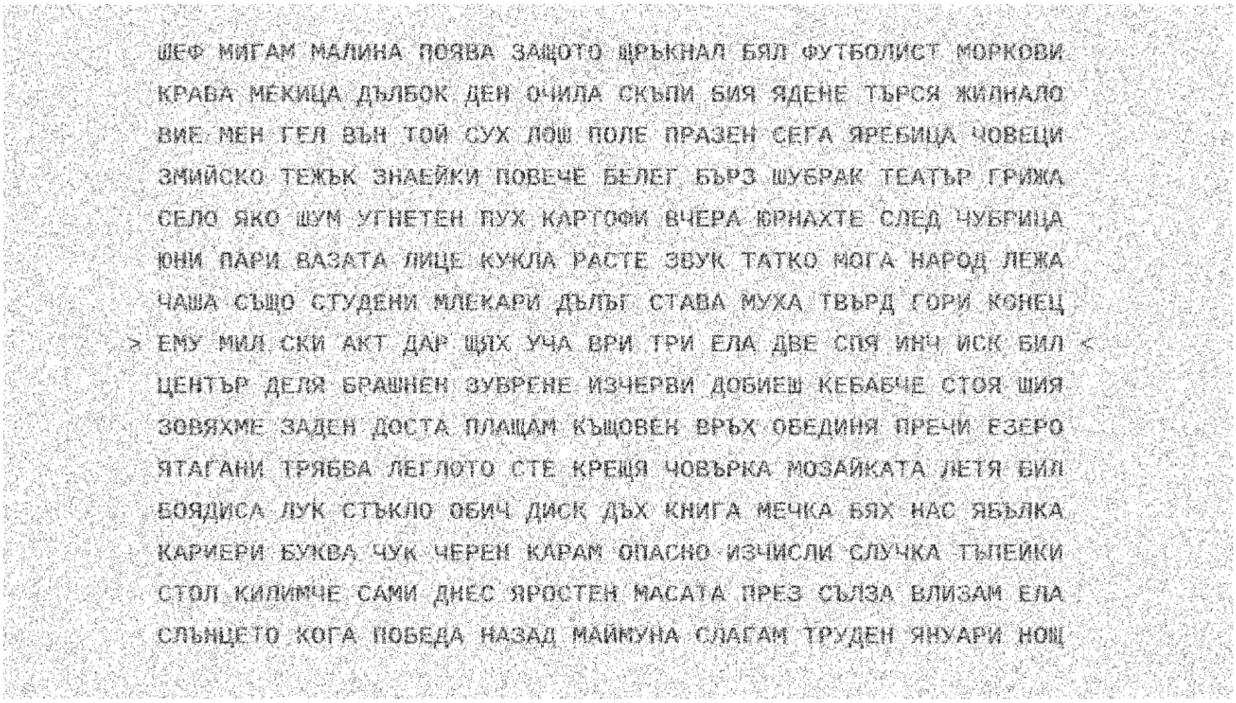

Figure 1. Example of the word stimuli at the noise level of 55%. The change in presentation scale affects the image appearance.

account for heteroskedasticity in the data, we used the package glmmTMB (Brooks et al., 2017). In all models, we used the group as a between-group factor.

We tested different random effects for the error number and the reading speed (represented as the time needed for reading a single letter string) to account for the correlation in individual data caused by the repeated testing of the participants. To evaluate the relation between reading accuracy and speed, we used a generalized mixed model on the proportion of errors weighted by the number of read words using as fixed factors the noise level, the letter number, the letter string type, and the time needed for reading a single letter tring. The noise level was considered a categorical factor. We used the glmmTMB package with a beta-binomial distribution as the proportion of errors is a continuous variable in the range (0, 1). We tested random intercept and random slope models to account for the correlation between the individuals in their repeated testing.

The model selection was determined by the Akaike information criterion (AIC). Model assumptions for the selected models were verified using the package DHARMa (Hartig, 2021). It allows testing for over-and under-dispersion, outliers, and uniformity of the residuals.

The post-doc analyses of the results were performed by emmeans package (Lenth, 2021). The results of these analyses are summarized after the presentation of the effects' significance.

The package effects (Fox and Weisberg, 2019) were used to evaluate the effect of the predictors on the dependent variables.

The data and the scripts for their exploration and analysis are available at https://zenodo.org/record/5843561

Results

We enumerated the cases when the children omitted to read a word and divided the read letter strings (words and pseudowords) into correct, incorrect, or corrected. In addition to these accuracy measures, we evaluated the reading speed using the time for reading a single item as a metric. We present successively below the analyses of these measures to trace the difference in the performance of the groups with developmental disorders compared to the control group with TD.

Reading difficulties – errors, misses, and corrections

Not all children have read all lines in a sample page. Out of 252 missed lines (6.56% from all samples), 145 cases are for children with ADHD (8 participants, 30 – for a child who refused to read, and 115 – for the rest of the children), 88 cases – for children from the DD group (10 children), 13 – for the group with ASD (two children), and 6 –for the TD group (one child). The unread lines were observed predominantly for pages with longer strings and depended little on the noise level. The cases with missing lines were excluded from further analyses.

The children's errors in reading included letter replacements, intrusions, misplacements, and omissions. We disregarded the number of errors in reading a single letter string

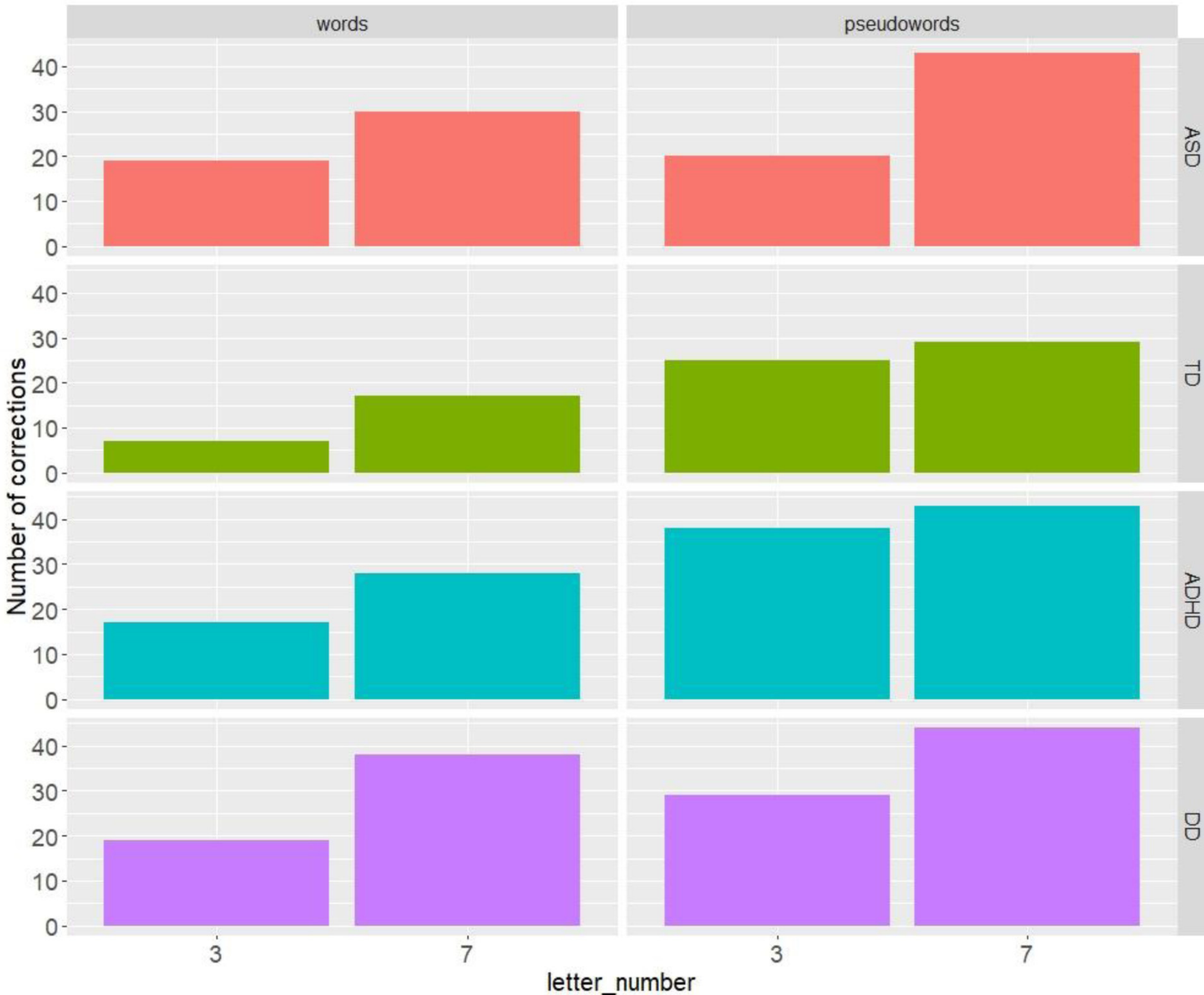

Figure 2. Barplot of the corrections for the 3-letter and the 7-letter words and pseudowords.

and only marked it as incorrectly read. Occasionally the children also made corrections or missed some letter string in a line. About 20% of the read letter strings were corrected. More corrections were performed for pseudowords and the longer letter strings (Figure 2). The TD group made the least number of corrections.

Error analysis

We wanted to know whether there were differences among the tested groups of participants concerning the effect of the experimental factors: letter string length and type and noise level on the number of errors in the reading. The distribution of the error count for different noise levels and groups is presented in Figure 3. The figure shows that the distribution shape changes primarily due to the different number of correctly read words (error count = 0).

To evaluate the effect of the experimental factors on the error number, we applied a Poisson generalized mixed model to the error count. We used a random intercept model to account for the correlation among the individuals due to their repeated testing. We used a zero-inflation model to account for the probability of having extra zeros not being generated by the model fixed factors. The best-fitting model was a zero-inflated Poisson model that specifies the error count to vary with the group, the letter string length and type, the noise level (considered as a categorical factor), and their interaction. The zero-inflation term varies with the letter number and the noise level. An offset term accounts for the differences in the number of read words in the different conditions and groups.

A detailed table of the estimated model parameters, standard errors, confidence intervals, and p-values is included as Supplemental material (Table S2). The modelling results show significant effects of all main factors at $p < .05$ ($\chi^2(1) = 12.94$; $p = 0.004$ for the group; $\chi^2(4) = 722.78$; $p < .001$ for the noise level; $\chi^2(1) = 551.01$; $p < .001$ for the string type; $\chi^2(1) = 400.87$; $p < .001$ for the letter number).

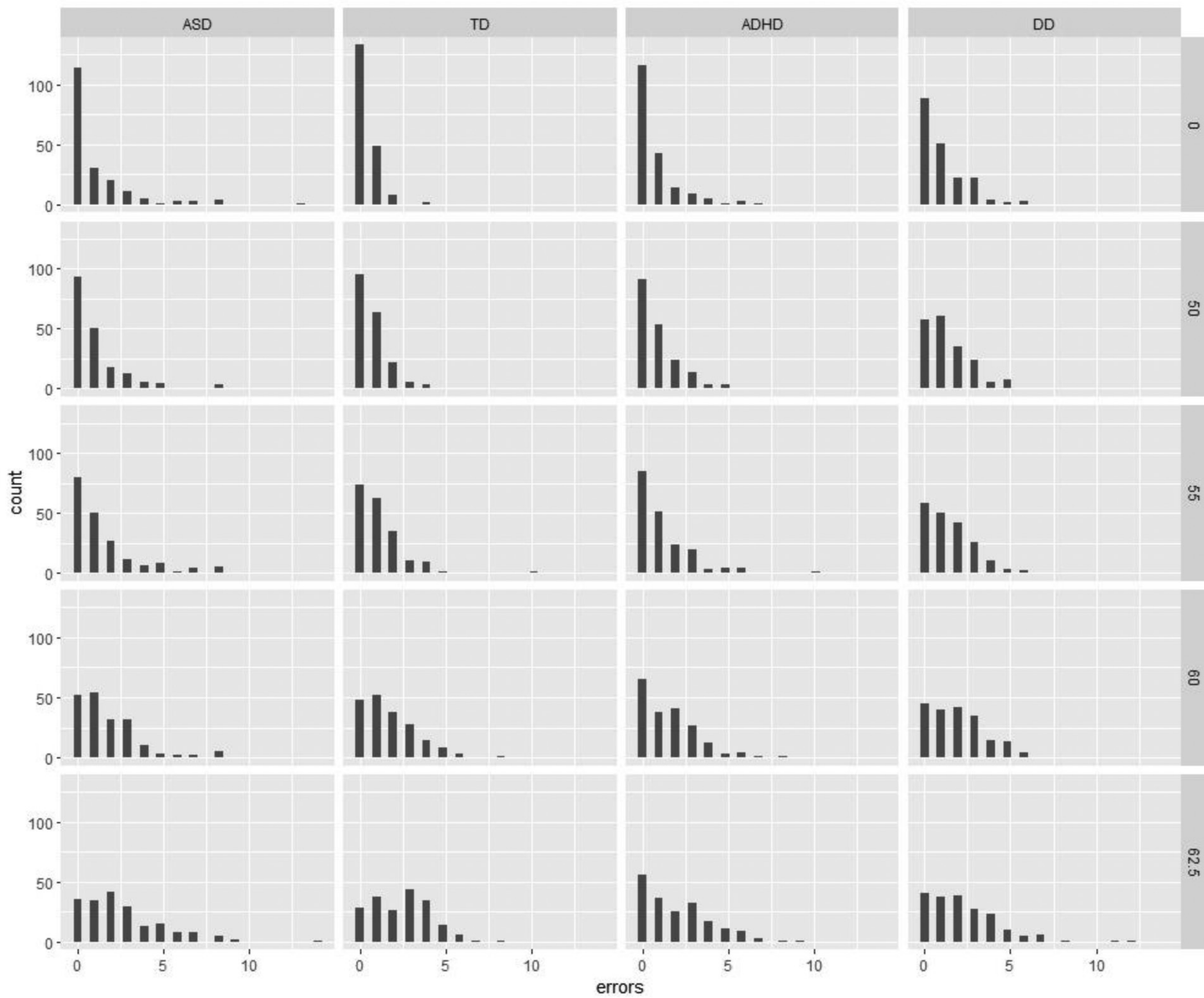

Figure 3. Error distributions at different noise levels.

Overall, the TD group makes the least errors, whereas the DD group makes the most. The number of errors increases with the noise level and the letter string length. The errors are higher when reading pseudowords than words. Only the double interactions between the noise level and the string type and between the string type and the letter number are significant at $p < .05$ ($\chi^2(4) = 18.14$; $p = 0.001$). They reflect the increased difference in error count between pseudowords and words and between long and short letter strings with the increase in the noise level. The interaction between the group, noise level, and the string length is significant due to the opposite effects of the noise levels on the error count for short and long strings. The difference in error number between the groups is less at high noise levels when reading long letter strings, whereas, for short strings, the difference is minimal at low noise values. Figure 4 shows the dependence of the error number on the experimental factors.

Time per word

The distributions of the time for reading a single letter string are skewed and varied in spread and shape depending on the experimental factors – group, added noise level, length, and the type of the presented letter strings (Figure 5). The variability in the reading time per string in a single condition represents the individual differences between the members of each group predominantly. The variability is highest for the DD and the ADHD group. The ASD group is the only group with less reading time per string variability than the TD group, and this effect occurs predominantly for longer words and pseudowords.

To evaluate the effect of the experimental factors on the reading time per single letter string, we applied a generalized mixed model regression with the number of letters, the letter string type, and the noise level as categorical predictors and the group – as a between-group factor.

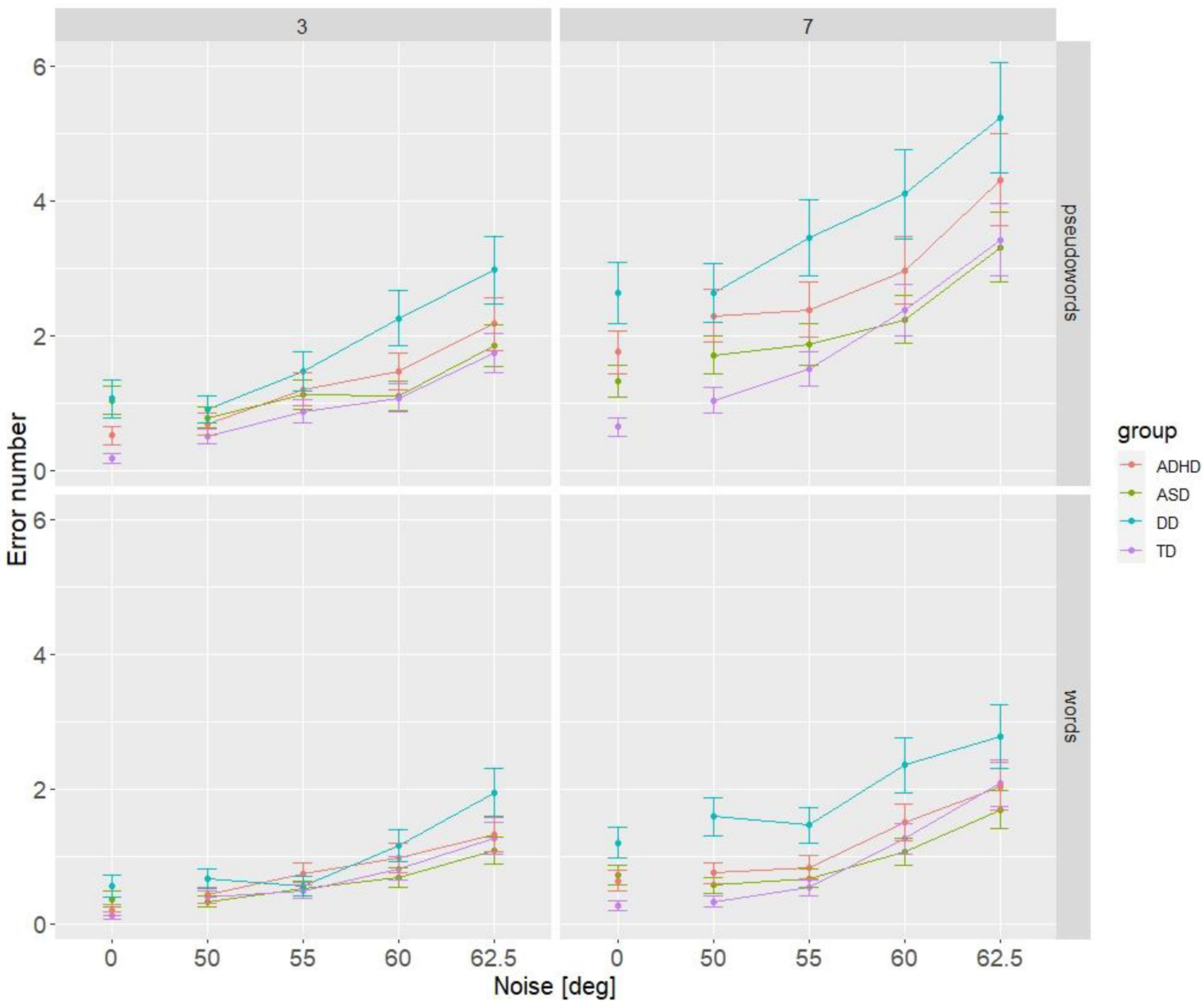

Figure 4. Fitted dependence of the error number for the different groups on the letter number, and string type. The error bars show the standard errors of the estimates.

We considered the noise level categorical as the graphical representation of the mean reading time per word showed a non-linear dependence on the noise level. The participants' age was included as a continuous predictor.

We first tested which distribution family best describes the changes in the estimated reading time. The best fitting of the models we considered was the one with Gamma distribution and log link. We fitted a varying slope model to account for the correlation in the individuals in repeated sampling and a dispersion parameter to account for the unequal variance of the distributions. The random and the dispersion terms included the within-subjects factors: noise level, letter number, and letter string type.

A detailed table of the estimated model parameters, standard errors, confidence intervals, and p-values is included in the Supplemental Material (Table S3). All main effects and most of the double interactions are significant at $p = .05$ ($\chi^2(1) = 8.38$; $p = 0.03$ for the effect of group; $\chi^2(4) = 249.08$; $p < .001$ for the effect of noise; $\chi^2(1) = 64.78$; $p < .001$ for the string type; $\chi^2(1) = 878.80$; $p < .001$ for the letter number; $\chi^2(1) = 16.76$; $p < .001$ – for the age of the participants). The non-significant interactions between the group and the string type ($\chi^2(1) = 6.63$; $p = .08$) and between the group and the letter number ($\chi^2(1) = 7.80$; $p = .08$) suggest that the string type and the letter number affect the reading speed of the groups differently. The significant interactions between the group, the string length and its type, and between the group, the string type, and the noise level imply more complex interference between these factors.

Overall, the ASD group has the shortest reading time that differs insignificantly from the mean reading time of the TD group, while the longest reading time is for the DD group. The reading time (Figure 6) increases with the noise level and is longer for the pseudowords and longer letter strings. It is reduced with the age of the participants. The relative change in reading time with the increase of the noise level is most prominent for the TD group and least –

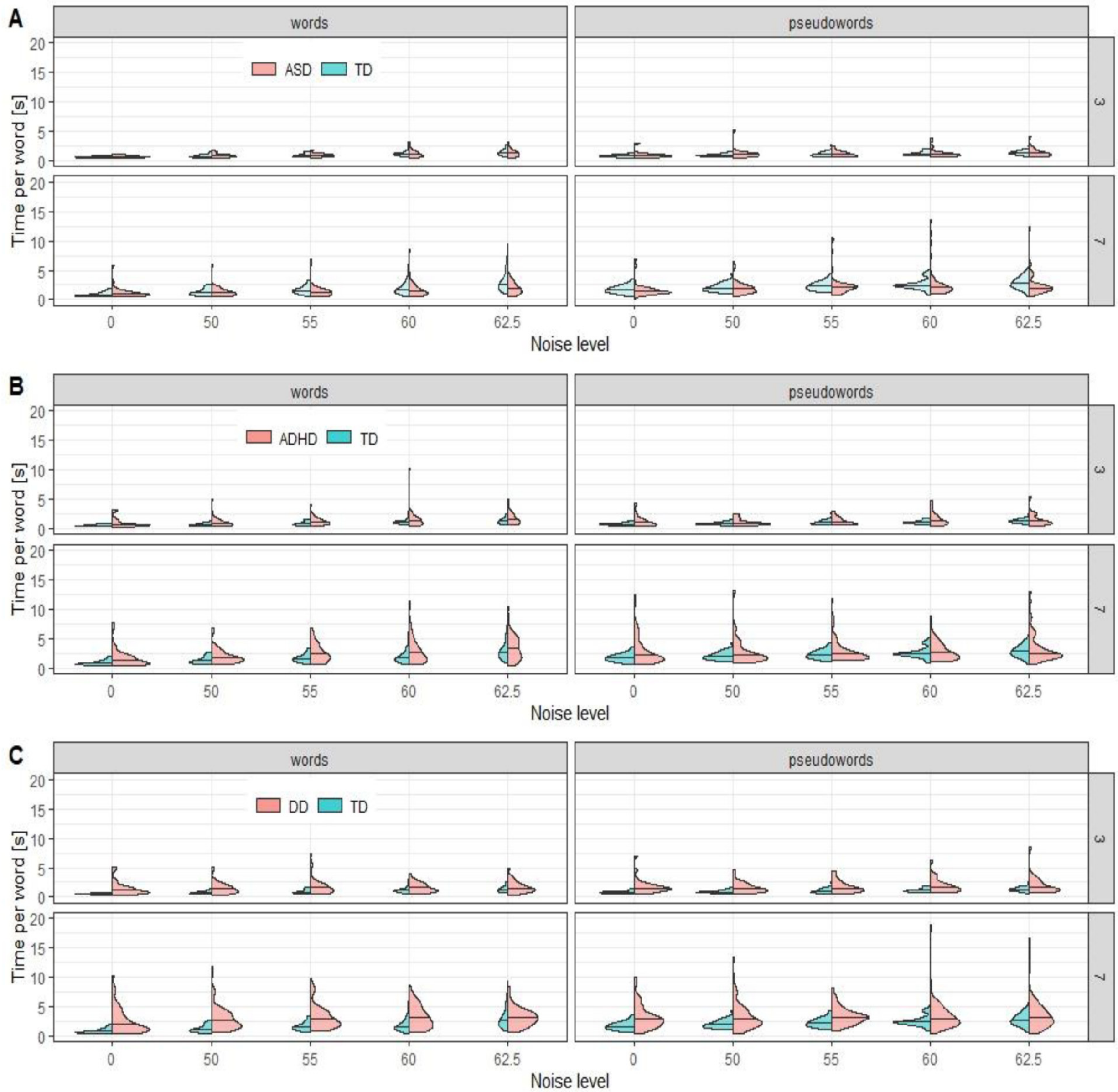

Figure 5. Distributions of the reading time per string for the separate groups with developmental disorders compared to the TD group. The median is also shown.

for the ASD group. The DD group time per string differs from the TD and ASD group at all noise levels irrespective of the string type and length.

Based on the post-hoc analysis, several conclusions could be drawn: The prolongation of the reading times for pseudowords is larger for longer than for short strings. The difference in the time for reading words and pseudowords diminishes with the increase in the noise level. The reading time for pseudowords and words does not differ significantly for all groups at the highest noise level (Figure 7). For the DD group, the reading time for words and pseudowords differs significantly only at the 0 noise level. For this group, the reading time for pseudowords is independent of the noise level, irrespective of the string length. Also, reading longer words takes significantly less time in the no-noise condition than at other noise levels. The reading time increases relatively most for the TD group for words than for pseudowords at the highest noise level. The difference in reading time for words and pseudowords was less pronounced for the ASD at low noise levels and disappeared for all groups at the highest noise level (Figure 7).

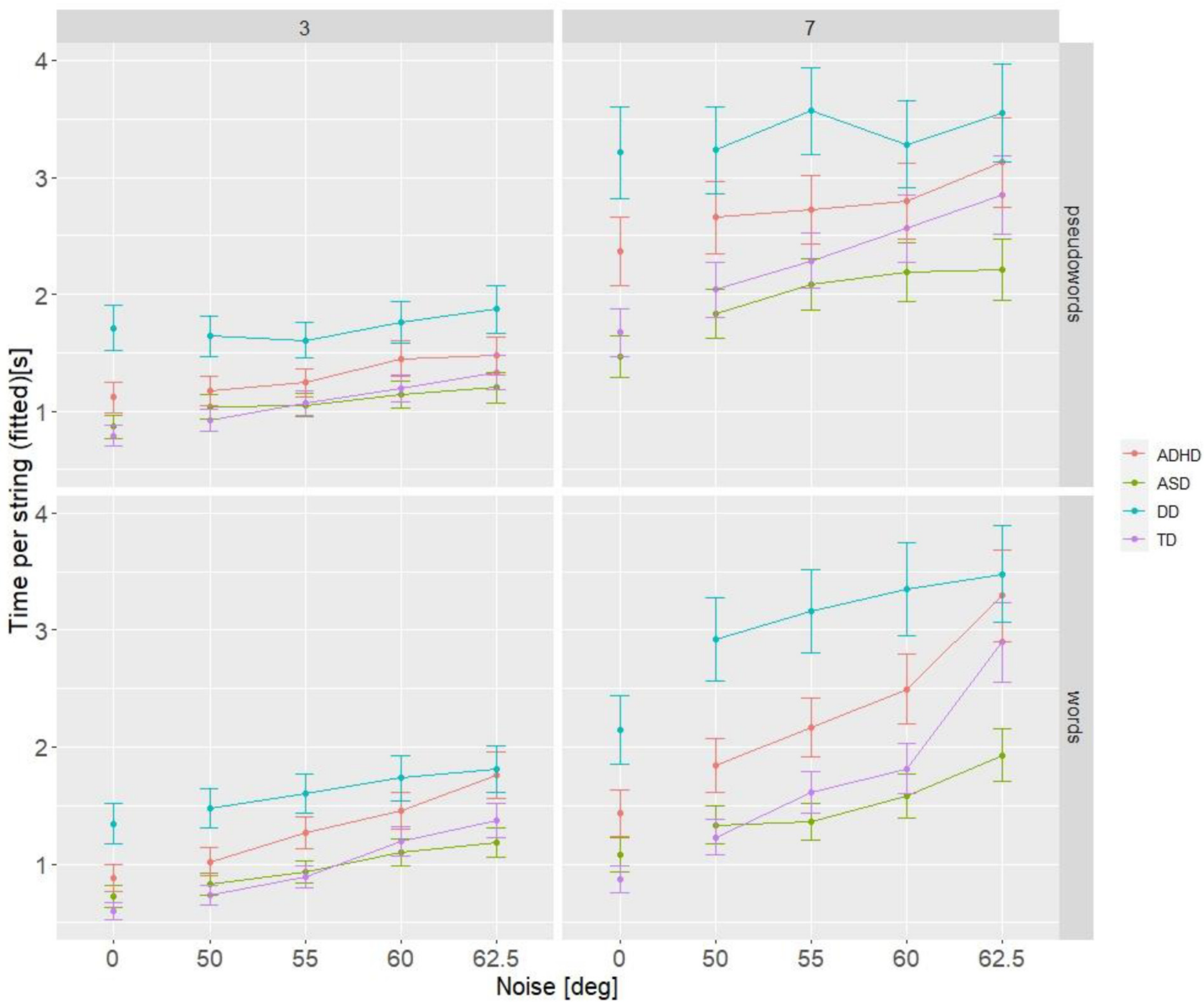

Figure 6. Fitted dependence of the reading time per letter string for the different groups, letter number, and string type.

Effect of reading speed on accuracy

We wanted to know whether the reading accuracy is affected by the reading time and, if so, whether there are differences or similarities in group performance. We tested the effect of the number of letters, string type (words or pseudowords), the group, the noise level, and the time per string on the proportion of correct responses and their interactions. The noise level was considered categorical as this improves the model's goodness of fit. The modelling results suggest that the logarithm of the time per word fits better the results than the raw time estimate. A random slope and intercept model best describes the results.

The modelling results show significant effects of all main factors ($\chi^2(1) = 52.41$; p < for the logarithm of reading time per word; $\chi^2(3) = 8.62$ for the group; p = 0.03; $\chi^2(1) = 142.65$; p <.001 for the letter number; $\chi^2(1) = 551.23$; p <.001 for the string type, and $\chi^2(4) = 669.61$; p <.001 for the noise level). Most of the higher interactions are non-significant.

There are differences between the groups depending on the letter number (interaction group: letter number $\chi^2(3) = 25.73$; p = .04), the type of the items (interaction group: string type $\chi^2(3) = 26.59$; p < .001), the logarithm of the time per word (interaction group: log(time per word) $\chi^2(3) = 15.25$; p <.001), and the noise level (interaction group: noise $\chi^2(12) = 21.35$; p = 0.04).

Figure 8 represents the fitted dependence of the proportion of correctly read strings on the response time for the different noise levels separately for words and pseudowords. The fitted curves are restricted to the maximal reading time per string for each group + 1 s. This representation allows demonstration of the reading time changes as the noise level increases. The figure lacks confidence intervals as the effects package could not estimate them correctly for the model used.

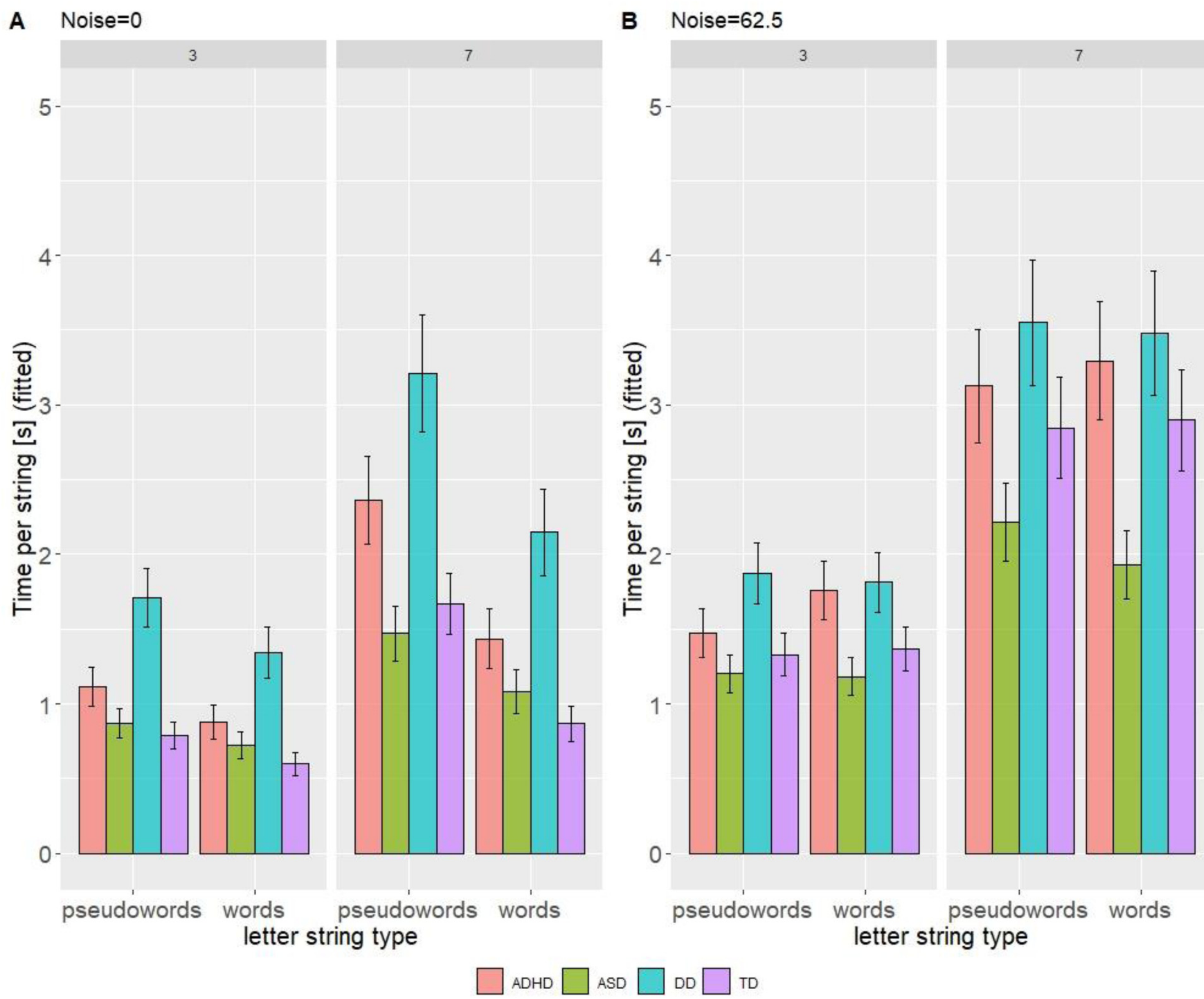

Figure 7. Reading time per letter string for the different groups, letter number, and the string type at noise levels 0 and 62.5.

It is clear that the longest reading time per group is not obtained at the highest noise level. Significant group differences exist in the relation between the reading accuracy, reading speed, and the noise level. At the lowest noise levels, the reading accuracy is predominantly independent of the reading time. The latter effect seems to represent the individual differences in the reading speed of the participants in the separate groups. There is a tendency for the reading accuracy to decrease with the prolongation of the reading time. However, an opposite effect is observed for the DD for pseudowords, with accuracy improving for slower reading speed.

The reading time exerts a more substantial effect on the accuracy of words than pseudowords.

Discussion

Usually, in perception studies, the zero level noise is considered a measure of the internal noise in task performance (e.g., Manning et al., 2017). However, reading is a complex process and is also limited by attentional allocation and eye movements (Dehaene, 2010), hence the no-noise condition in the present study cannot be regarded as an estimate of the inner noise. Instead, the no-noise condition could be considered as an assessment of optimal accomplishment. For such reason, we discuss the results in the no-noise and noise conditions separately.

Comparison between all the groups in the no-noise condition

In the no-noise condition, the group with TD showed the shortest time for reading words and short pseudowords, followed by the group with ASD, while their reading of long pseudowords was slightly slower than that of the ASD group. Moreover, the reading time variability was also lower for these two groups. The ASD group is the only group with less reading time per string variability than the TD group, and this effect occurs for the pseudowords.

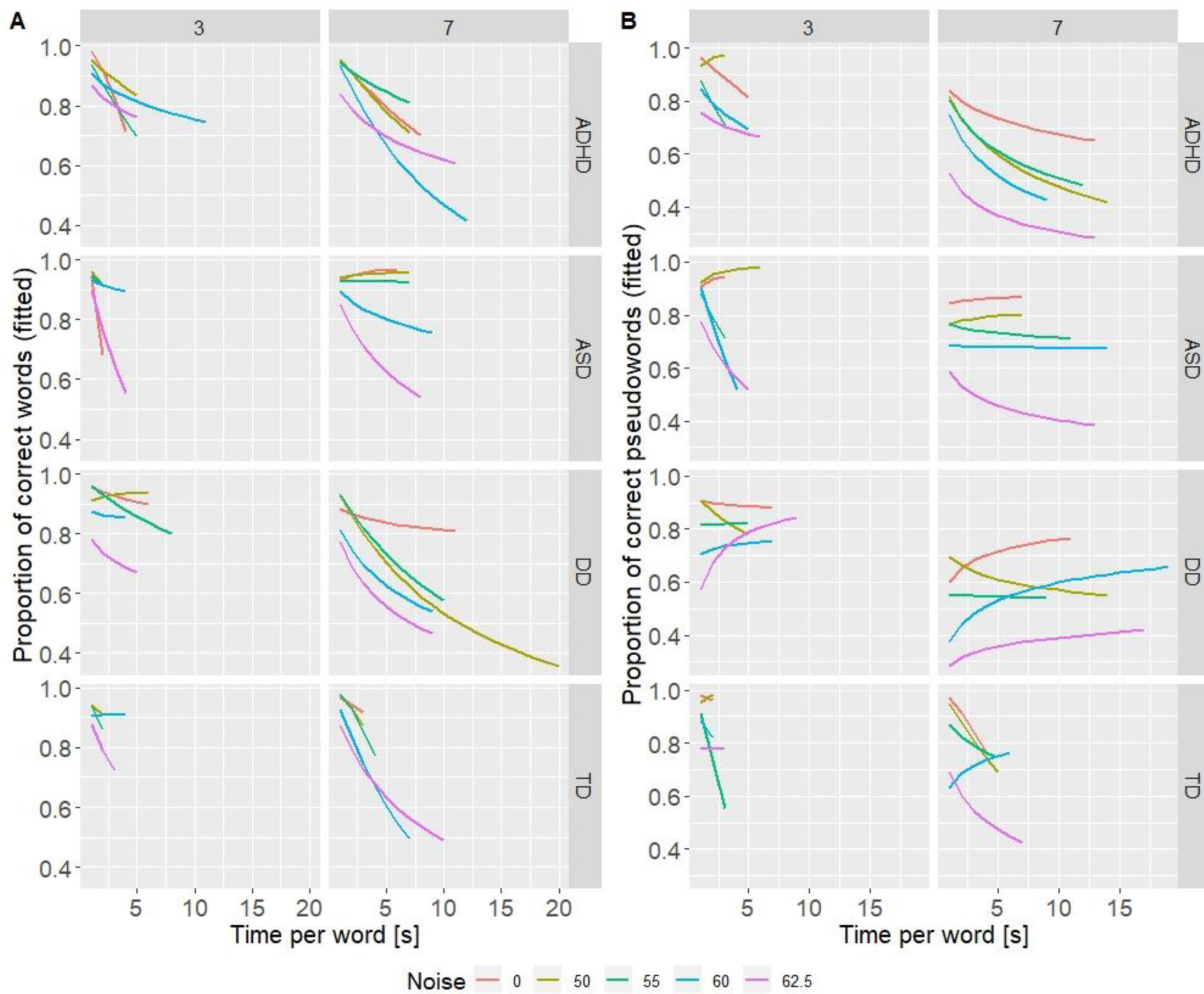

Figure 8. Fitted dependence of the proportion of correctly read words (A) and pseudowords (B) on the response time for the different noise levels.

The time for reading a single letter string is the longest for the group with DD followed by the group with ADHD. Also, the reading time variability is the highest in these two groups. The readers with DD and ADHD also have a greater number of misses. The proportion of errors is the highest again in the group with DD. However, in contrast to the slower reading times, the group with ADHD showed higher reading accuracy than the ASD group in most cases in the no-noise condition. The lowest proportion of errors was observed in readers with TD.

These results are generally in line with previous studies reporting that the reading performance (excluding comprehension) is within the average range for readers with ASD. Most studies that assess reading performance in ASD groups report similar reading results compared to TD groups (e.g., Nation et al., 2006; Gabig, 2010; May et al., 2015; Baixauli et al., 2021). However, when participants with lower cognitive functioning or comorbid conditions were not excluded from the group with ASD, reading performance was much worse, especially for participants with severe symptoms of autism (Nally et al., 2018; Åsberg & Sandberg, 2010). Although our group with ASD includes participants with various intellectual functioning and their IQ scores varied between 62 and 113, comorbid conditions were excluded in advance based on the most recent developmental and medical reports taken with the parents' consent. Although the reading time was similar for the ASD and TD groups in the no-noise condition of our study, the difference in the proportion of errors and some dissimilarities obtained in the relationships between all measures in the present research pointed to potential specifics of the reading process in the ASD group.

The much longer reading time found in the DD group was expected, as the participants from this group were gathered based on their reading problems. Our results agree with previous findings of considerably slower reading in dyslexia (e.g., De Jong & Van der Leij, 2003; Wimmer et al., 2002; Taroyan & Nicolson, 2009; Wijnants et al., 2012).

In most cases, the reading performance of the ADHD group resembled more that of the DD group than the performance of the TD and ASD groups because of the longer reading time and higher variability and proportion of errors in the no-noise condition. These results confirm previous reports about the reduced speed for reading words in the group with ADHD (Sciberras et al., 2014), and more reading errors in the ADHD groups compared to TD (Lobo & Lima, 2008). According to Tamm et al. (2014), children with ADHD and poor readers read slower, but there was no difference specifically in the separate aspects of reading. Our data also show some general impairment of reading abilities since the reading time was prolonged, and the proportion of errors was higher in the ADHD group compared to the TD group when reading words and pseudowords in both no-noise and high noise conditions.

All groups of participants read longer letter strings for a longer time. This observation could be related to the word-length effect, referring that the processing of a visual word is correlated with its length. This effect is well documented in pure alexia, and it is described in dyslexia (Zoccolotti et al., 2005; Martens & de Jong, 2006), but little is known about other disorders (Barton et al., 2014). The present study results did not show significant interactions between the factors of the group and letter number; the effect was marginal ($p = 0.05$). This finding could result from the wide age range of the participants in our study – between 8 and 16 years old, since the word-length effect decrease with the reading expertise. However, the interaction between the group, the letter number, and the string type was significant; the letter number affected the time for reading pseudowords more strongly than words in all groups of participants except the DD group. According to Ferrand (2000), the strong length effect reported in pseudoword naming results from the serial processing within the non-lexical route. Hence, the weaker difference in the length effect between words and pseudowords in the DD group may be due to problems with the transition from sublexical to a lexical reading of words in this disorder (Zoccolotti et al., 2005).

Effect of the external visual noise on the reading performance

The noise added to words or pseudowords alters the letters in the string and damages their local structure. Hence, at the high noise levels, the word templates do not match, and the process of letter encoding is disrupted. Since we used unrelated words, the readers could not take advantage of the text context. However, our manipulation kept the letter strings in a line clearly separated with spaces between them, allowing the preparation of proper eye movements. At low noise levels in reading words, the word context allows for improving letter identification.

The higher noise level increased the reading times and the proportion of errors in all the groups. The noise increase prolonged the reading time of the groups with TD and ADHD, while the word distortion affected the reading of the ASD group to a lesser extent. Even, at the highest noise level, the participants with autism read faster and made similar or even fewer errors than the participants with TD. Moreover, the difference between the reading time for words and pseudowords in the ASD group was the smallest compared to the other groups. If participants with autism use a different strategy to recognize and read the letter strings, this could probably be revealed by a detailed analysis of the error types and their number in a single word or pseudoword. It might imply less weight given to the direct pathway that recovers the identity and meaning of the word in typical reading conditions. This finding is in line with the suggested reduced activation of the lexical route in ASD in addition to the untypical activation of the sublexical route reported by Moseley et al. (2014).

Participants with DD continued to read with the most errors up to the highest noise level, especially for the long words and pseudowords. The minor effect of the visual noise on the reading time of the ASD and DD groups could hardly be connected with a potential better noise filtering and matching to the word percept because of the increasing amount of errors with the noise increase, especially for the group with DD. The added noise in our study destroys the form and context of a single word and diminishes the possibility of matching a proper word template. The groups with ASD and DD probably relied on a different reading strategy that is less susceptible to noise manipulations. This strategy is perhaps based on serial letter-by-letter reading, and it is supported by a more locally oriented visual processing style in autism (Van Eylen et al., 2018) and dyslexia (Franceschini et al., 2017).

The group with ADHD made more errors and read slower than the TD group at all noise levels except at the highest noise of 62.5%, when its reading performance equated to that of the control group. Lexical and sublexical routes are supposed to invoke different types of attention – reflective in the former case and voluntary – in the second one (Ekstrand et al., 2019). These differences in attention involvement may contribute to the inferior performance of the ADHD group at lower noise levels for which the lexical route should be dominant. The disrupted local visual structure and the higher attention demands, especially at high noise levels and for pseudowords could predict a suboptimal performance of the ADHD group. This group showed the most consistent negative relationship between the reading time and the proportion of errors – the accuracy dropped more with the time extent.

The reading of pseudowords took a longer time and was accomplished with more errors by all groups included in the study. These data agree with previous findings that participants with DD as well as typical readers show inferior accuracy and slower processing times for pseudowords than words (Wimmer et al., 2002; Taroyan & Nicolson, 2009). The prolongation in reading time for the TD group for words is steeper than for pseudowords with the noise level increase. The difference in reading time for words and pseudowords is less pronounced for the ASD and DD at low noise levels and disappeared for all groups at the highest noise level. These data imply that the transition between using lexical and sublexical pathways in reading could happen at a different point for each group in the study, probably earlier for the DD group. Indeed, the difference in reading time for words and pseudowords disappears at different noise levels for each group: 50% for the DD group, 55% for the ADHD group, 62.5% for the ASD and the TD groups, supporting such a suggestion. It could be supposed that the lexical information is hardly available at the highest noise level, and it is almost impossible to recognize a word as a holistic depiction. The words, corrupted by the high visual noise, could not probably be recognized by the lexical pathway since they no longer match the templates of the words from the lexicon memory. At this level, participants from all groups may use the sublexical pathway for reading pseudowords and words, causing the disappearance of the difference in reading time of these letter string types. These findings are in agreement with theoretical models about the lexical and sublexical route in reading and their atypical activation in ASD and DD.

Significant differences between the groups with different development were found in the relationship between the reading time, accuracy, and noise level.

Such complicated relationships between the parameters of reading performance and the external visual noise level could be connected not only to the specific features in the visual and phonological processing of written stimuli in the three disorders but also to their unequal abilities to process noisy sensory signals.

The processing of noisy sensory signals depends on the ability to filter the external sensory noise by matching the signal to a proper perceptual template. This ability preserves our perception stable, while suboptimal external noise filtering diminishes perceptual efficiency. As pointed out in the Introduction, the external noise filtering is probably compromised, especially in ASD and DD. Moreover, the perceptual efficiency could be further lowered by excessive quantities of neural or inner noise associated with random variations of neuronal activity reported in ASD, DD, and ADHD. Importantly, the findings in the previous studies imply that the increased inner noise is usually connected to the stimulus processing and was described only during sensory responses but not at the resting state in conditions of autism (Milne, 2011; Dinstein et al., 2012; Weinger et al., 2014; Haigh et al., 2015) and dyslexia (Hornickel and Kraus, 2013). In contrast, the larger neural response variability is not necessarily tied to a specific sensory or cognitive neural process but rather due to more variable ongoing neural processes and acts continuously in ADHD (Gonen-Yaacovi et al., 2016; Machida et al., 2019). Many facts about the combination of effects of the external noise filtering (Sperling et al., 2005; 2006; Park et al., 2017) and the precise place of action of the increased inner noise are still not clear. Nevertheless, it is possible to suggest that they could influence differently multiple stages in the reading process in ASD, DD, and ADHD, consequently leading to the described reading specifics in each disorder.

The manipulation of the low-level visual features in the present study degrades the visual input. It allows separating the reading performance of the ASD, ADHD, DD, and TD groups differently than in the no-noise condition. The reading time, accuracy, and the relationship between these measures changed distinctly for each group. Further detailed research analysis of the error types according to the frequency of the words, the first and last syllables or considering them as parts of the speech would allow understanding of the word template choice and how it differs among the groups. It would also allow better identification of the transition between the lexical and sublexical routes. We have already started such an endeavor to compare the error types according to the above-listed criteria for the groups with ASD and TD (Shtereva et al., 2021) with promising results. The results of that analysis could provide a base for clinical implications and could help to improve educational strategies by appropriately structuring the learning process of children with TD, ASD, ADHD, and DD.

Conclusions

Using visual noise that distorts the letter identity allowed us to differentiate the reading performance of the groups with ASD, ADHD, and DD, compared to the control group with TD not only in the no-noise condition but also with the visual noise increase. In all conditions, readers with DD showed the worst reading performance with the longest reading time and the highest proportion of errors. Readers with TD always had the shortest time and the lowest proportion of errors. In almost all conditions, the ASD and the control group have similar reading performance, while the results of the group with ADHD were closer to those of the group with DD. The dissimilarity in reading abilities of the groups with different development is most evident when the accuracy and reading speed were linked together. It could result from diverse external noise filtering and internal noise levels in the separate groups with developmental conditions. The minor noise effect on the reading of participants with ASD and DD probably imply atypical usage of the sublexical pathway. At the highest noise level, all groups of participants possibly read real words by relying on the sublexical pathway, which is usually included in the reading of pseudowords.

Even though the design of our study was not suitable to explore reading comprehension, a thorough analysis of the error types of the groups with different development and their distribution as parts of speech made by the separate groups of participants would shed light on this issue as well.

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Supplemental material

Supplemental material for this article is available online.

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