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Phonological deficit and (lack of) visual attention deficit in developmental dyslexia

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Abstract

The most widely accepted cause of developmental dyslexia is a deficit of phonological processing, i.e. a difficulty in processing of speech sounds. Although children with dyslexia show low phonological skills as a group, there are individuals with dyslexia who present typical phonological skills. One of the alternative theories claims that dyslexia is caused by a limited visual attention span. This deficit results in a smaller number of letters which can be processed at one glimpse, and therefore leads to slow reading pace.

The main aim of the current thesis was to examine the phonological and the visual attention span deficits among Polish children with dyslexia. The thesis covers topics of the prevalence, time stability, and the neural correlates of the deficits, as well as describes two interventions addressing them.

In Experiment 1, we found that about 39% of children with dyslexia had a phonological deficit, which was stable over time. The visual attention span deficit was present only in 6–15% of individuals, it was not stable over time and the level of visual attention span was only slightly related to reading abilities. In Experiment 2, we found that the development of the phonological brain network during the first years of education differs between typical readers and children who develop dyslexia. Typically reading children activated structures responsible for phonological processing already at the beginning of education, and showed a reduced brain activation over time. However, children with dyslexia presented a delay in the development of phonological structures. In Experiment 3, we compared the efficiency of two trainings, based on attentional video games and phonological non-attentional video games in children with dyslexia. Both training groups improved reading speed and accuracy. However, the reading progress did not differ significantly from the progress made by a group who did not participate in any training. Thus, the noted improvement in reading in the experimental groups could be attributed to regular reading development. Finally, in Experiment 4, we verified a method of enhancing reading in children based on an increase of inter-letter spaces and found that it indeed somewhat improved reading accuracy in dyslexic (and not in typical) readers, although it had no impact on reading speed.

We conclude, that a phonological deficit is relatively frequent in Polish children with dyslexia, stable over time and difficult to cure with a training based on video games. Phonological difficulties have a visible neural background, as dyslexic readers present a delay in the development of the brain phonological network. However, we failed to replicate the visual attention span theory of dyslexia. Not only the visual attention span deficit is rare in Polish children, but also it is not stable over time. The training based on attentional video games could not help dyslexic readers read better, and the increase of inter-letter spaces also resulted in a smaller improvement of reading performance than expected.

Streszczenie

Powszechnie uznaną teorią dotyczącą przyczyn dysleksji rozwojowej jest teoria deficytu przetwarzania fonologicznego, zgodnie z którą osoby z dysleksją nieefektywnie przetwarzają dźwięki mowy. Chociaż jako grupa dzieci z dysleksją wykazują niskie umiejętności fonologiczne, są jednak wśród nich osoby o typowym poziomie umiejętności fonologicznych. Jedna z alternatywnych teorii dysleksji głosi, że trudności w czytaniu mogą wynikać z ograniczeń pojemności uwagi wzrokowej. Te ograniczenia mają zmniejszać liczbę przetwarzanych jednocześnie liter i tym samym spowalniać czytanie.

Głównym celem niniejszej pracy było zbadanie deficytów fonologicznych i pojemności uwagi wzrokowej wśród polskich dzieci z dysleksją. Praca obejmuje tematykę częstości, stabilności czasowej i mózgowego podłoża tych deficytów, oraz metod interwencji ukierunkowanych na te deficyty.

W pierwszym badaniu stabilny w czasie deficyt fonologiczny znaleziono u około 39% dzieci z dysleksją. Deficyt pojemności uwagi wzrokowej był obecny tylko u 6–15% dzieci z dysleksją i niestabilny w czasie, a pojemność uwagi wzrokowej była tylko nieznacznie związana z poziomem czytania. W drugim badaniu stwierdzono, że mózgowe podłoże przetwarzania fonologicznego zmienia się w pierwszych latach edukacji, a jego rozwój różni się pomiędzy dziećmi typowo czytającymi i dziećmi z dysleksją Dzieci typowo czytające aktywowały struktury odpowiedzialne za przetwarzanie fonologiczne już na początku edukacji i z czasem wykazywały zmniejszoną aktywację mózgu podczas przetwarzania fonologicznego. Natomiast dzieci z dysleksją wykazywały opóźnienie w rozwoju struktur fonologicznych. W trzecim badaniu porównano skuteczność dwóch treningów, opartych na uwagowych i fonologicznych grach komputerowych u dzieci z dysleksją. Po przeprowadzeniu obu treningów zaobserwowano wzrost zarówno tempa, jak i poprawności czytania. Jednak postępy w czytaniu w obu grupach treningowych nie różniły się znacząco od postępów poczynionych przez dzieci z dysleksją, które nie uczestniczyły w żadnym treningu. Tak więc zauważoną poprawę w czytaniu w grupach eksperymentalnych można przypisać zwyczajnemu rozwojowi umiejętności czytania. W ostatnim badaniu zweryfikowano skuteczność metody poprawy czytania, bazującej na zwiększeniu odstępów między literami w tekście, i stwierdzono, że w pewnym stopniu poprawiła ona poprawność, ale nie tempo czytania u dzieci z dysleksją.

Podsumowując, deficyt fonologiczny występuje dość często u polskich dzieci z dysleksją, jest stabilny w czasie i trudny do terapii za pomocą gier komputerowych. Trudności fonologiczne mają wyraźne podłoże mózgowe, jako że dzieci z dysleksją wykazują opóźnienie w rozwoju mózgowej sieci fonologicznej. Natomiast deficyt pojemności uwagi wzrokowej występuje u polskich dzieci z dysleksją rzadko i jest niestabilny w czasie. Żadna z wykorzystanych metod bazujących na usprawnianiu przetwarzania wzrokowego nie przyniosła oczekiwanych skutków w terapii dysleksji.

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Glossary of abbreviations

AVG	attentional video games
CON	control group
CONDYS	control group with dyslexia
DYS	group with dyslexia
fMRI	functional magnetic resonance imaging
HG	Heschl gyri
IFG	interior frontal gyrus
IPL	inferior parietal lobule
MTG	middle temporal gyrus
NAVG	non-attentional video games
PNAVG	phonological non-attentional video games
PrCG	precentral gyrus
RAN	rapid automatized naming
SD	standard deviation
SMG	supramarginal gyrus
SPL	superior parietal lobule
ST	superior temporal gyrus
TP	time point

Preface

The present thesis aims at verifying two theories of developmental dyslexia: phonological deficit and visual attention span deficit theories.

Part I is devoted to describing the state of the art, in particular:

Chapter 1 describes the phonological deficits in dyslexia,

Chapter 2 presents the research on visual attention span deficit in dyslexia,

Chapter 3 explores the links between the phonological and the visual attention span deficits, and

Chapter 4 shows the possible treatments of dyslexia based on the phonological or visual attention trainings.

Part II presents the original studies done for the purposes of the thesis.

Chapter 5 presents the rationale for the Experiments presented in Chapters 6 – 9.

Chapter 6 is devoted to searching for phonological and visual attention span deficits in children with dyslexia, and to assessing their time stability.

Chapter 7 describes the neural bases of phonological deficit in dyslexia.

Chapter 8 examines phonological and attentional interventions based on video games,

Chapter 9 verifies possible ad-hoc treatment based on inter-letter spacing.

Chapter 10 discusses the obtained results.

Introduction

Since the beginnings of research on developmental dyslexia, the most challenging issue has been to learn why some children with typical intellectual skills and sufficient educational environment fail to acquire fluent reading skills (Ramus, 2003). In alphabetic languages, learning to read involves learning the relations between visual symbols or sequences of symbols (such as graphemes, syllables or words) and the relevant sounds or sequences of sounds (such as phonemes, syllables or words; Phillips et al., 2008). Thus problems in either visual processing or in processing of speech sounds may theoretically result in difficulties in learning to read (Saksida et al., 2016). These two potential sources of reading impairment, a visual and a phonological disruption, are the main topic of the current thesis.

The first part of the thesis is divided to a description of the phonological theory (Snowling, 1998) of dyslexia, which is the predominant one, and the visual attention span theory of dyslexia (Bosse et al., 2007), that remains one of the alternative theories. In the next Chapter, I review findings on the coexistence of the two deficits among children with dyslexia. The descriptions of the theories are accompanied by previous findings on the neurobiological correlates of the deficits in dyslexia, as well as by results of studies which aimed at remediating dyslexia with a phonological or visual attention trainings.

In the second part of the thesis, I describe four experiments in which we studied the phonological deficit and the visual attention span deficit theories of dyslexia. In the first experiment, we searched for the two deficits in two groups of children with dyslexia. As we failed to find a group of children with visual attention span deficit, and this deficit was unstable over time, in the further studies we looked for the neural basis of the phonological deficit only (Experiment 2) and resigned from searching for the neural correlates of the visual attention span deficit. The last two experiments presented in the thesis have a more applied nature.

Namely, in Experiment 3 and Experiment 4 we tested remediation strategies aimed to improve the reading skills of children with dyslexia. Experiment 3 describes an attempt to treat dyslexia with a training based on video games, aimed either at mastering phonological or at developing visual attention skills. Finally, Experiment 4 describes an ad hoc attempt to make reading easier for children with dyslexia by increasing inter-letter spaces in texts. As such ad hoc method is impossible for phonology, i.e. although we can change the print in which we write words, we cannot change the phonological patterns of those words, the Experiment 4 was limited to replication of studies on visual attention.

In the second part of the thesis, I present data from a total of 336 participants (participants of the Experiment 2 were a subsample of Experiment 1b, and participants of the Experiments 3 and 4 were recruited from those who participated in Experiment 1a). If we summed up the time of testing and training sessions attended by these participants in the four experiments, we would obtain over 3600 hours in total, i.e. 150 days of consecutive testing. Obviously, gathering so much data would be impossible for one person (even for a very dedicated PhD student). Therefore the vast majority of the research presented in the current thesis was done in close cooperation with other members and collaborators of the Laboratory of Language Neurobiology. The list of people who contributed to the research presented in the current thesis includes: mgr Anna Banaszkiewicz, mgr Katarzyna Chyl, dr Agnieszka Dębska, mgr Gabriela Dzięgiel-Fivet, prof. dr hab. Anna Grabowska, mgr Agnieszka Kacprzak, dr hab. Artur Marchewka, mgr Joanna Plewko, dr Marcin Szczerbiński, dr Jakub Szewczyk, lic. Marta Wójcik, and mgr Agata Żelechowska. The contribution of the collaborators included supervision (AG), co-design of the experiments (KC, AD, AG, AK, AM, JP, MS, MW), co-design of the tools used in the experiments (KC, AD, AK, JP, MS, JS, MW) data collection, coding and double checking (AB, KC, AD, GDF, AK, JP, MW, AŻ), as well as support in data analyses (KC, AD) and discussions of the obtained results (KC, AD, AG, AK, JP, MS, MW).

The idea of taking together the four experiments, data analyses for the current thesis, as well as the whole writing were done by myself.

Some parts of the experiments and results presented in the second part of the current thesis have been published in research journals. Previous publications included the design and results of the Experiment 2 (Łuniewska et al., 2019) presented in a wider context of familial risk for dyslexia, and the design and results of the Experiment 3 (Łuniewska et al., 2018). The design and results of the Experiment 4 have been submitted to a journal (Łuniewska, Wójcik & Jednoróg, submitted).

Part I: State of the art

Chapter 1. Phonological deficit in dyslexia

The first described example of developmental dyslexia was published over 120 years ago (Morgan, 1896). This case study reported a ‘well-grown lad, aged 14’, Percy, who was unable to learn to read despite being a bright and intelligent boy. While reading, Percy could only recognize highly frequent words such as ‘the’ or ‘and’, but he was making mistakes in almost all other words. While writing, the boy was making specific errors. For instance, he wrote ‘scojock’ instead of ‘subject’ or ‘seasow’ instead of ‘seashore’. Modern researchers would assess these errors as typical for dyslexia, and would explain them saying that people with dyslexia suffer from poor phonological representations affecting both the way how they read and how they write (Snowling, 1998). This Chapter presents the current state of knowledge on the phonological deficit in dyslexia.

Phonological awareness

Phonological awareness is the ability to recognize, identify or manipulate any phonological units within words (Ehri et al., 2001; Torgesen et al., 1994; Ziegler & Goswami, 2005). These phonological units include phonemes, i.e. sound units which distinguish one word from another (e.g. ‘p’ and ‘b’ in English in words ‘pig’ and ‘big’), syllables or some groups of phonemes (e.g. first two phonemes of a word). Several years of studies across different languages have shown that early phonological awareness is a strong predictor of reading acquisition (Bishop & Adams, 1990; Bradley & Bryant, 1983; Elbro et al., 1998; Georgiou et al., 2008; Holopainen et al., 2001; Kirby et al., 2003; Moll et al., 2016; Schatschneider et al., 2004; Schneider et al., 1997; Snowling & Melby-Lervåg, 2016), i.e. the higher the phonological skills at the beginning of the education, the better the reading skills after several years of schooling.

This strong relation between the level of phonological awareness at preschool or early school age and further reading scores is relatively easy to explain. Children's knowledge that words are made up of smaller parts such as syllables and phonemes makes it possible for them to understand the 'code' of written language and to learn what is the correspondence between the sounds of spoken language and letters or combinations of letters (Phillips et al., 2008). In other words, without the ability to divide the spoken words into single sounds it would be impossible to write these words down, and the other way around: without the ability to combine the read phonemes it would be impossible to read whole words.

On the other hand, the difficulties with phonological awareness can be observed in some children already at preschool age (or even earlier; Richardson et al., 2009), and preschoolers who present low phonological skills are more likely to have symptoms of dyslexia several years later (Elbro et al., 1998; Wimmer, 1996). Also school-age children, adolescents and adults with dyslexia show low phonological awareness (see review in the next sections). These difficulties with phonological processing present in people with dyslexia are the core of the phonological deficit theory of dyslexia (Snowling, 1998).

How to measure phonological skills?

The tasks typically employed in assessment of phonological awareness depend on the level of expected phonological abilities of the studied sample, as the phonological awareness develops typically from the awareness of whole words to awareness of smaller bits, such as syllables and phonemes (Phillips et al., 2008). A model of phonological functions (Krasowicz-Kupis et al., 2015) with phonological tasks corresponding to them is illustrated on the Figure 1. The earliest phonological functions and the easiest phonological tasks are illustrated at the top, whereas the later tasks and the more demanding tasks are presented at the bottom of the Figure.

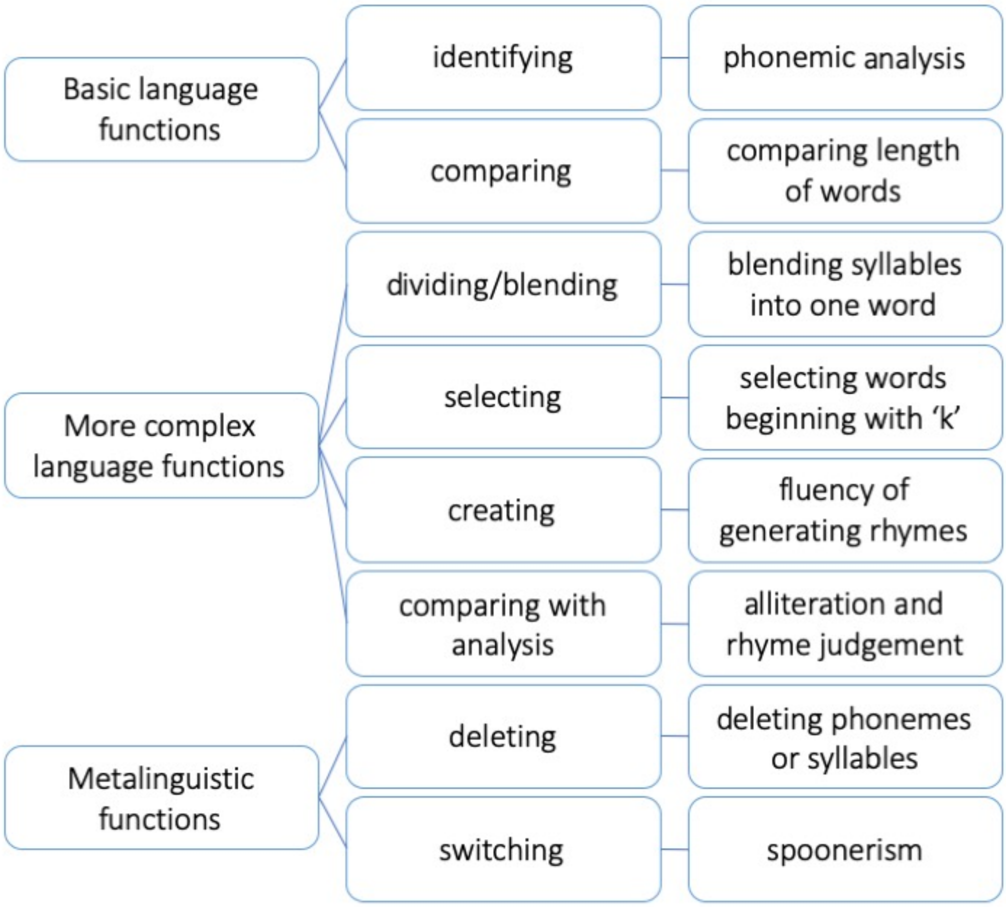

Figure 1. Model of phonological functions by Krasowicz-Kupis (adapted from Krasowicz-Kupis et al., 2015, p. 9).

Whereas for preschool children such tasks as rhyme comparison (i.e. assessment whether two words rhyme or not) or alliteration identification (i.e. assessment whether two words begin with the same sound) may be already too demanding, in adult studies it is more common to use spoonerisms (i.e. a task in which participants are asked to transpose the onset sounds of two words, e.g. ‘doctor, window’ would become ‘woctor, dindow’). The typical tasks used in studies on children at school age include more basic tasks such as phoneme or syllable blending (i.e. children are asked to blend the heard phonemes into one word), as well as more difficult tasks such as phoneme deletion (i.e. children are asked to repeat a the word without a given sound, e.g. say ‘banana’ without ‘b’, or say ‘bring’ without ‘r’).

These tasks although typically used in both research on phonological processing and in diagnosis, still could pose some problems, as the performance in the phonological tasks may be influenced by reading skills (Morais & Kolinsky, 2005). This happens because phonological awareness is not a naturally emerging skill, as for instance, other language abilities such as knowledge of vocabulary or grammar (Ramus, 2001b). The development of phonological awareness may rather depend on teaching and practice, similarly as the development of reading (Goswami, 2002). As in some families children start learning to read before beginning formal education, phonological awareness in preschoolers and children attending first grades of primary school may depend on home literacy practices (Burgess et al., 2002; Foy & Mann, 2003). It was also established that the level of reading abilities at the beginning of education may be a predictor of growth in phonological skills in the following year (Nation & Hulme, 2011).

Phonological skills of poor readers across languages

The biggest challenge in mastering phonological awareness is that phonemes do not naturally exist in spoken language (Phillips et al., 2008). While speaking, we do not pronounce each individual phoneme. Instead, in human speech we can observe co-articulation of speech sounds, i.e. single phonemes are affected by the preceding, subsequent (or both) ones. For instance, the way how we pronounce the phoneme corresponding to the letter ‘n’ differs between the words ‘again’, ‘uncle’ and ‘input’. Similarly in Polish we pronounce ‘w’ differently in words such as ‘wakacje’ and ‘wstać’.

The strength of the correspondence between the phonemes and the graphemes (letters or combinations of letters) defines the concept of language transparency (Frost et al., 1987;

Seymour et al., 2003). The 'transparent' (or 'shallow') languages are those in which the correspondence between the phonemes and graphemes is straightforward, and Polish can be used as an example here. On the other hand, in the 'opaque' (or 'deep') languages the correspondence is not so stable: the same graphemes may correspond to several phonemes, and several graphemes may correspond to the same phoneme, which is the case of English of French (Frith et al., 1998; Landerl et al., 1997; Wimmer & Goswami, 1994; Ziegler et al., 2003).

The transparency of the orthographic system has an impact on the pace of reading acquisition (Defior, 2004). It also affects the phonological development, as phonological decoding skills are learned earlier in transparent than in opaque languages (Frith et al., 1998) and the final stage of phonological awareness may differ between languages, being intrasyllabis units in opaque and phonemes in transparent orthographies (Defior, 2004). In particular, in transparent languages it is easier to develop an awareness of phonemes at a very early stage of reading acquisition, due to the visible correspondence between letters and sounds (Goswami, 2002). Some researchers argue that in transparent orthographies phonological difficulties in poor readers may be observed only at the beginnings of education, but they disappear in the first years of schooling (Landerl & Wimmer, 2000; Wimmer, 1996), which is not the case of opaque languages where phonological problems are still present even in adolescents adult readers with dyslexia (Wilson & Lesaux, 2001). However, other research suggested that the remission of the phonological awareness difficulties in dyslexic learners of a transparent orthography is an artefact of the used test, and if more age-appropriate tasks are employed, the deficit in phonological abilities is visible also in older groups (de Jong & van der Leij, 2003). The idea that in transparent orthographies reading is less dependent on phonological skills than in opaque ones is further supported by cross-linguistic longitudinal studies, in which phonological skills are a stronger predictor of reading in opaque than in transparent languages (Georgiou et al., 2008).

On the other hand, some cross-linguistic studies show that a deficit in phonological processing is universal in dyslexia across both transparent (here: Italian) and opaque (French, English) languages (Paulesu et al., 2001). Another study suggested that reading skills can be predicted by phonological awareness in languages of high (Finnish, Hungarian), medium (German, Dutch) and low transparency (English, French), but the strength of the predictions was the highest in the opaque orthographies (Landerl et al., 2013). Also phonological deficits have been observed in dyslexic readers in several transparent languages, such as Czech (Caravolas & Volín, 2001), Dutch (Morfidi et al., 2007), Finnish (Kortteinen et al., 2009), Portuguese (Germano et al., 2014) or Spanish (Bednarek et al., 2009; Goswami et al., 2011; Serrano & Defior, 2008). Previous studies on Polish show that independently from age readers with dyslexia present lower phonological skills than typical readers, and evidence was found for children (Krasowicz-Kupis et al., 2009; Lipowska et al., 2008), adolescents (Wieczorek et al., 2016) and adults (Bogdanowicz et al., 2014; Reid et al., 2007). Despite the fact that the previous reports show that phonological skills of Polish readers with dyslexia are lower than those of their peers, it is not clear what is the frequency of the phonological deficit among Polish children with reading impairment. So far, a huge heterogeneity of profiles of Polish adults with dyslexia was reported (Reid et al., 2007): in a group of 15 adult dyslexics, nine people showed an isolated phonological deficit, but other deficits or combination of deficits was exhibited by no more than three people. The existing research cannot answer the question about the time-stability of the phonological difficulties of this group either.

Neural basis of phonological deficit in dyslexia

The number of functional resonance imaging (fMRI) studies which searched for differences in phonological processing between typical readers and children with dyslexia has been intensively growing in the last decade. These studies typically employed rhyme judgement or phoneme deletion tasks (Dębska et al., 2016). Typically, children and adolescents with reading impairment present a hypoactivation of tempo-parietal cortex, posterior superior temporal sulcus, inferior frontal gyrus, inferior temporal gyrus and bilateral superior temporal gyrus in the left hemisphere (Bolger et al., 2008; Cao et al., 2006; Desroches et al., 2010; Tanaka et al., 2011; Temple et al., 2001; van Ermingen-Marbach et al., 2013). These hypoactivations of the left hemisphere structures were also confirmed by meta-analyses (Richlan et al., 2009, 2011). The common flaw of the mentioned studies is that the participants were asked to perform phonological operations on the words presented visually. The need to read the stimuli could affect the results, as participants with dyslexia struggled to read the words. Pure phonological processing as assessed with spoken stimuli was a topic of only few studies (Dębska et al., 2016, 2019; Desroches et al., 2010; Kovelman et al., 2012; Raschle et al., 2012; Yu et al., 2018). The results of these studies are inconsistent, as children with dyslexia were either reported to present a hypoactivation of the left fusiform gyrus (Desroches et al., 2010), or only a hypoactivation of the left dorsolateral prefrontal cortex (Kovelman et al., 2012).

We are already aware that when children acquire reading, this learning process modifies the way how their brains process language (Dehaene et al., 2015). This change happens because the new experience with letters supports the development of more advanced phonological skills (Bentin, 1992). What we do not know is how acquisition of reading influences the neural network responsible for phonological processing. So far, the cross-section studies on children at different ages showed an increase of activation of the brain during phonological processing with age (Brennan et al., 2013; Cone et al., 2008). Typically developing English speakers showed an age-related increase of activation in the left dorsal inferior frontal and temporal gyri (Brennan et al., 2013; Cone et al., 2008) and inferior parietal cortex (Brennan et al., 2013). However, as the reported studies were cross-sectional, the age-related effects could also result from some other between-group differences independent from age. The only longitudinal study which explored the development of the phonological brain network showed a decrease of activation with age in the left inferior parietal cortex and bilateral precuneus (Yu et al., 2018). This study assessed the correlates of phonological processing measured with alliteration (first phoneme) assessment task in children at three time points: before children started education, after the first year of education and two years later. The authors explained the observed decrease of the brain activation by a specialization of the phonological network (Yu et al., 2018). According to the Interactive Specialization Theory (Johnson, 2000, 2001, 2011), cognitive functions are initially subserved by multiple brain pathways which consist of different regions and are particularly sensitive to given type of stimuli. As a result of learning, eventually only the pathways optimal for the stimuli processing are activated. It is worth mentioning that the participants of the only longitudinal study were typical readers and therefore it is still unknown how the phonological network develops in children with dyslexia.

Chapter 2. Visual attention span deficit in dyslexia

As not all children with dyslexia present a phonological deficit (White et al., 2006), there are several alternative theories concerning cognitive causes of dyslexia (Ramus, 2001a; Ramus et al., 2003). According to one of the theories, developmental dyslexia may be caused, in some cases, by a limited visual attention span (Bosse et al., 2007; Bosse & Valdois, 2009; Valdois et al., 2004). This Chapter presents the theoretical background of the visual attention span deficit in dyslexia, the methods typically used for visual attention span assessment, as well as the results of the previous research on this topic.

The visual attention span is defined as the number of visual elements, such as letters or objects, which can be processed in parallel (Goswami, 2015; Lobier & Valdois, 2015). This number tends to be reduced in some dyslexic individuals, which results in difficulties in allocating attentional resources simultaneously for the processing of a series of visual stimuli. The mechanism responsible for the slower reading of children with limited visual attention span is described by the multitrace model of polysyllabic word reading (Ans et al., 1998).

The multitrace model of polysyllabic word reading

The idea that some children with dyslexia present insufficient visual attention span has its origin in the multitrace model of polysyllabic word reading (Ans et al., 1998). This model provides a theoretical description of the role of visual attention processes in reading. In particular, the model explains how a damage of the visual attention processes may result in impaired reading. According to this model, there are two possible reading procedures (or modes): a global and a an analytic one. The difference between the two modes lies in the kind of phonological and visual attention processing engaged in reading. The crucial feature of the model is the incorporation of a visual attentional window (VAW; Figure 2). The visual attentional window is used to extract the information from the orthographic input, and the size of the involved VAW differs between the two reading modes. In the global mode, the visual attentional window covers the whole sequence of the letters, e.g. a whole word. This large size of the VAW allows a simultaneous analysis of the whole input with a low phonological short-term memory load. Namely, in the global procedure the entire phonological output is generated in a single step. In other words, in the global reading mode whole words (or even larger items such as word combinations) are read simultaneously, at one glance.

However, in the analytic mode, the VAW is limited to only a part of the orthographic input. The analytic mode involves a sequential shifting VAW from left to right (in languages which use this direction of reading and writing), and subsequent parts of the input are processed successively. Each group of letters that fall within the VAW generates a phonological output, until the VAW reaches the end of the letter string. This procedure results in a high phonological short-term memory load, as previously generated phonological output must be stored and remain available at the end of processing. In other words, in the analytic mode it is possible to read just some bits of words and then the reader must combine these bits into a word.

The global mode always happens first, and the analytic procedure may be only used in case of failure of the global procedure. According to the authors of the model (Ans et al., 1998), a moderate limitation of the size of visual attentional window results in a disrupted reading in the global mode. The moderate damage of the VAW leads to, so called, surface dyslexia (see Chapter 3), i.e. reading impairment in which children have particular difficulties with irregular words, that are processed less automatically. The more severe the reduction of the VAW size, the more severely impaired reading, affecting both pseudowords and regular words.

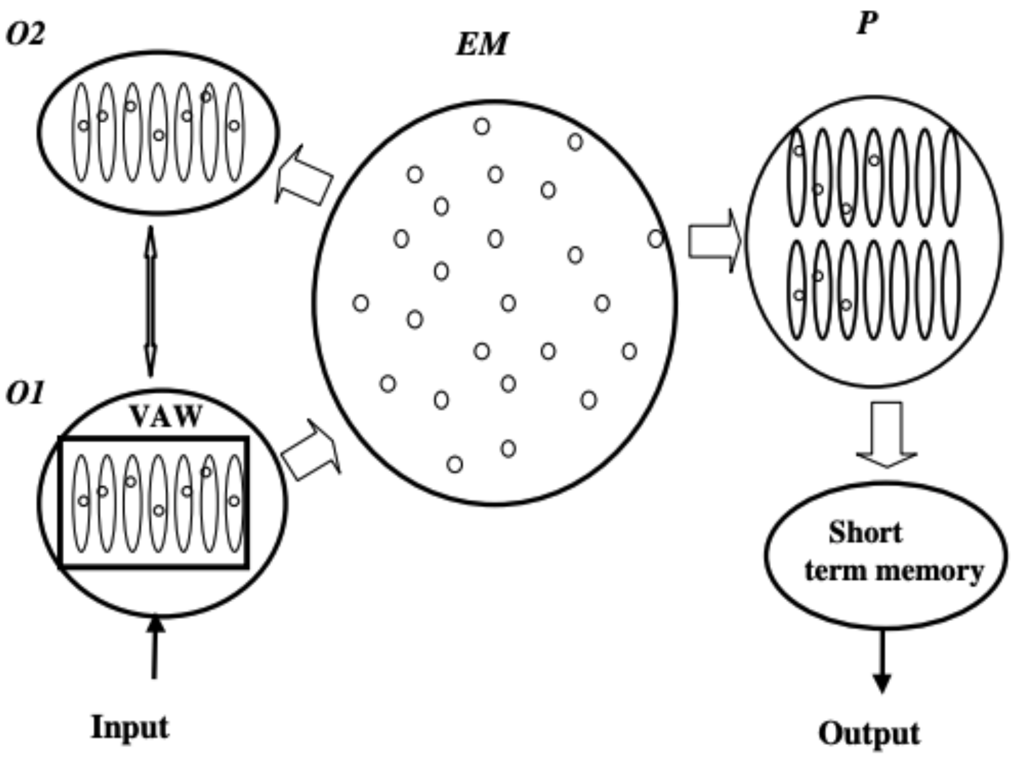

Figure 2. The multitrace connectionist model of reading (Ans et al., 1998). The picture source: Bosse et al. (2007). O1 - orthographic input layer, O2 - orthographic echo layer (which represents only the information from VAW in O1), EM - episodic memory, P – output phonological layer, VAW – visual attention window.

How to measure visual attention span?

The first case study on visual attention span in children with dyslexia applied two tasks (Valdois et al., 2003), variants of which were later on used in the majority of experiments on visual attention span deficits. These two tasks included a whole (global) report task and a partial report task (see Figure 3). In the global report task, a series of consonant strings is presented at the center of the screen for a short time (typically 200 ms). The strings are usually 5-item-long (e.g. B L T F M) and they are built up from 10 consonants (e.g. B, P, T, F, L, M, D, S, R, H).

The strings include no repeated letters (e.g. B P T P L), and no skeletons of real words (e.g. C M P T R for 'computer'). The stimuli are balanced in the way that each letter appears at each position the same number of times. The distance between adjacent letters is large enough to reduce crowding. At the start of each trial, a central fixation point or cross is displayed for 1000 ms, and either followed by a blank screen or directly by a letter string. After 200 ms of presentation of the string a mask (e.g. # # # # #) may be presented, though some experiments did not include it. The participants task is to report immediately after the presentation as many letters as they remember. In the global report task, the assessment concerns only the identification of stimuli, and not their position in the string.

The partial report task uses the same stimuli, i.e. 5-item strings built up from the same 10 letters. The procedure of stimuli exposure is also the same as in the global report task. However, after the string disappears, a cue targeting one of the five positions appears on the screen. The cue may for instance be an underline symbol or a vertical line. In the partial report task, participants are asked to report only the cued letter.

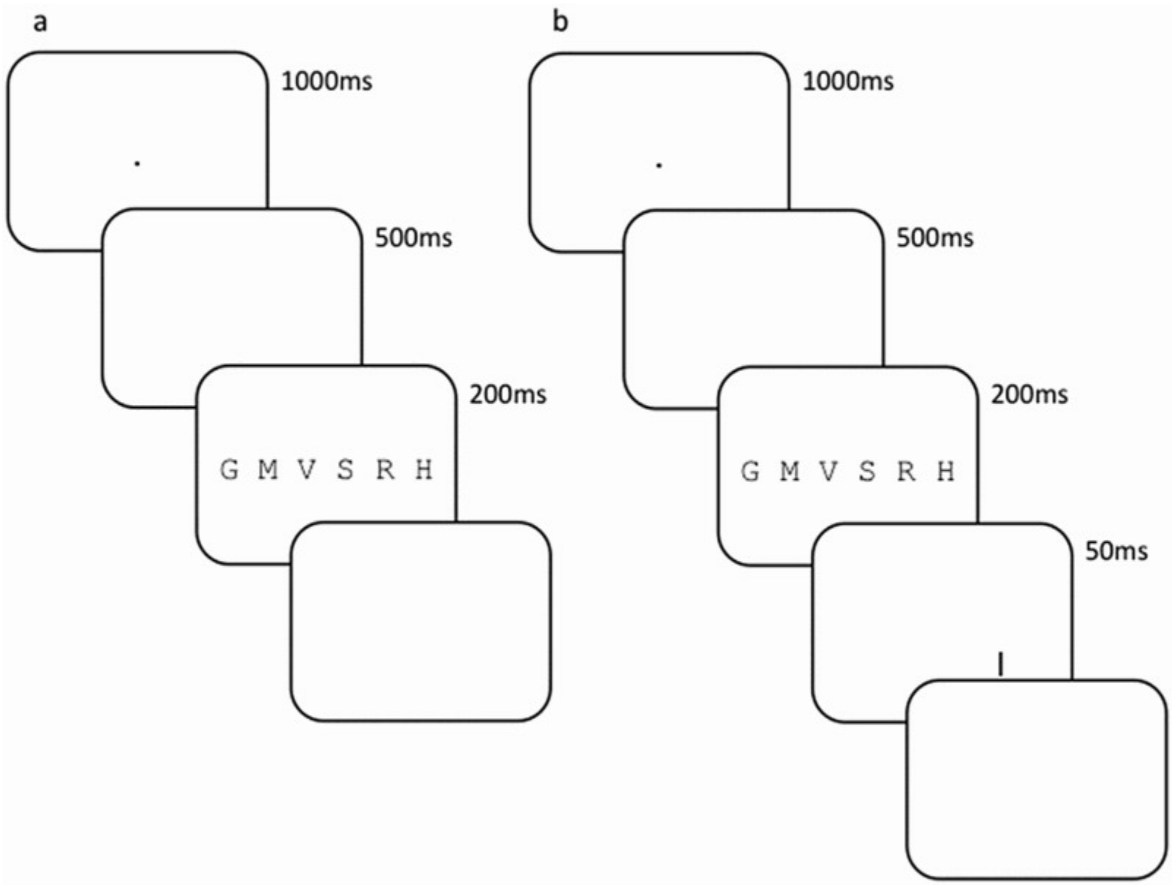

Figure 3. Tasks used to assess visual attention span: (a) global report condition, (b) partial report condition. The picture source: Frey & Bosse (2018).

In the initial studies participants were asked to report the stimuli orally (Bosse et al., 2007; Frey & Bosse, 2018; Hawelka et al., 2006; Hawelka & Wimmer, 2005; Valdois et al., 2003), i.e. after seeing a letter string the participants' task was either to name as many presented letters as possible (global report task), or to name the letter presented at the cued position (partial report task). Similarly, the majority of subsequent research included oral reports from participants (Germano et al., 2014; Lallier et al., 2014; Lallier, Thierry, et al., 2018; Lassus-Sangosse et al., 2008; Lobier et al., 2012; Valdois et al., 2012; Yeari et al., 2017; Zoubrinetzky et al., 2014, 2016); see (Banfi et al., 2018) for review). However, in some other studies no oral reports were used, and an alternative forced choice task or array recognition tasks were applied instead (Banfi et al., 2018; Collis et al., 2013; Hawelka & Wimmer, 2008; Jones et al., 2008; Pammer et al., 2004; Shovman & Ahissar, 2006; Yeari et al., 2017; Ziegler et al., 2010). As the participants of these studies were asked to select the seen stimuli from a broader set (with size differing between two and nine elements) and not to name them verbally, the stimuli applied could be nonverbal, such as symbols (Banfi et al., 2018; Jones et al., 2008; Pammer et al., 2005; Yeari et al., 2017; Ziegler et al., 2010), letters from the Georgian alphabet unfamiliar to the participants (Shovman & Ahissar, 2006), or pseudoletters (Hawelka & Wimmer, 2008). The distinction between the oral reports and the other tasks is important because the type of stimuli applied in the task may indeed affect the results (see the next section).

Evidence for the visual attention span deficit in dyslexia

The initial reports on the limited visual attention span in children with dyslexia came from case studies (Valdois et al., 2003). The pioneering description of the dyslexic children with visual attention span deficits led to studies in which the visual attention span was compared between the typical readers and participants with dyslexia, both children and adults. The between-group comparisons showed that dyslexic teenagers and young adults needed longer presentation time to process the visual stimuli than typical readers (Hawelka et al., 2006; Hawelka & Wimmer, 2005). Also, the accuracy in oral global report and partial report tasks was lower in children with dyslexia than in typically reading controls, when letters or digits were used as stimuli (Bosse et al., 2007; Germano et al., 2014; Lallier et al., 2014; Lassus-Sangosse et al., 2008; Lobier et al., 2012; Valdois et al., 2012; Yeari et al., 2017; Zoubrinetzky et al., 2014). However this result was not replicated, when adult readers with and without reading impairment were compared (Lallier, Thierry, et al., 2018).

The limited visual attention span in dyslexia seems also less pronounced when nonverbal tasks are applied. In particular, the application of a nonverbal assessment of visual attention span typically showed no difference between dyslexic and typically reading adults (Hawelka & Wimmer, 2008; Shovman & Ahissar, 2006; Yeari et al., 2017) or children (Banfi et al., 2018). Crucially, several studies pointed at an interaction between group and the type of stimuli: the difference between typical readers and participants with dyslexia was visible only when letters or digits were reported, but not in case of colours (Valdois et al., 2012) or symbols (Collis et al., 2013; Ziegler et al., 2010). This interaction may suggest that children with dyslexia have deficits in visual processing of verbal material, such as letters and digit strings, but not nonverbal material, such as symbols. The specificity of the between group differences to the verbal material may suggest that in fact the limitations of the visual attention span in dyslexia are a result of the restricted experience with alphanumeric stimuli, i.e. restricted reading experience, rather than a cause of reading difficulties.

Does the visual attention span deficit depend on the orthography?

Both the visual attention span and its impact on reading may differ across languages. The existence of such differences suggests that the influence of the visual attention span skills on reading may depend on depth of orthography. In a cross-linguistic study on adult monolingual skilled readers (Awadh et al., 2016), visual attention span abilities were lower in Arabic speakers as compared to French and Spanish speakers who presented a similar level of performance in visual attention span tasks. The authors suggested that the limited visual attention span of the Arabic speakers may result from the higher complexity of Arabic letters (Awadh et al., 2016), which are more difficult to recognize than Latin letters (Awadh et al., 2016; Eviatar & Ibrahim, 2014). More crucially, the study found that although visual attention span skills correlated with reading abilities in French, there was no such relation in Spanish or Arabic (Awadh et al., 2016).

An interesting body of evidence on the impact of orthographic transparency on the visual attention span comes from the studies on bilingual populations. Such studies make it possible to assess the impact of readers' visual attention span skills on their reading performance in both languages, which may differ in transparency. For instance, a study which investigated letter string processing in English monolingual and Welsh-English bilingual adults, showed that bilinguals presented a disadvantage in visual attention span measured on letter stimuli (Lallier et al., 2013). The authors suggested that this disadvantage resulted from the experience with reading in Welsh (the heritage language of the participants) which has a shallow orthography. As experienced readers of a shallow orthography, the bilinguals perhaps presented a tendency to rely on smaller orthographic units in reading (Lallier et al., 2013). In contrast, monolingual English readers, who were used to a deeper orthography, processed larger orthographic units, as it is necessary to process more letters in parallel while reading in English.

Similar findings were reported in studies on Basque-Spanish and Basque-French bilinguals (Antzaka et al., 2018; Lallier et al., 2016). These children either were learning to read in two shallow orthographies (Basque and Spanish) or in one shallow and one deep (Basque and French). French-Basque bilingual children presented a wider distribution of visual attention than Spanish-Basque bilinguals (Lallier et al., 2016), suggesting that they focus on larger orthographic units. The subsequent study replicated these outcomes indicating that reading in the deep French orthography resulted in a larger bias towards the multi-letter processing (Antzaka et al., 2018).

On the basis of the previous studies, it is difficult to tell whether Polish children with developmental dyslexia should present visual attention span deficits. On one hand, the studies on bilingual populations suggest that the experience with a transparent orthography could lead to more severe visual attention span deficit (Antzaka et al., 2018; Lallier et al., 2013, 2016). These results are supported also by visual attention span deficit in Brazilian Portuguese (Germano et al., 2014), a language with a transparent orthography. On the other hand, the research on monolingual populations typically found a visual attention span deficit rather in dyslexic readers of opaque orthographies such as English and French (Bosse et al., 2007; Jones et al., 2008; Ziegler et al., 2010), whereas no differences between typical and dyslexic readers were found in German (Banfi et al., 2018; Hawelka & Wimmer, 2008).

Neural basis of visual attention span

Although there is much research on the brain correlates of the phonological processing in dyslexia (see the previous Chapter), the number of studies concerning the neural basis of the visual attention span deficit is very limited. The majority of the studies on this topic are case reports (Peyrin et al., 2012; Valdois et al., 2019; Valdois et al., 2014). The case studies on the neural basis of the visual attention span deficit suggest that this deficit may originate from an disrupted functioning of the superior parietal cortex. However, case reports are less valid and reliable than group comparisons (Riege, 2003) and the results of such studies are more difficult to generalize.

So far, only one study compared brain activation of French children with dyslexia who presented a severe visual attention span deficit and typical readers, during a visual attention task (Peyrin et al., 2011). The visual attention span deficit in the dyslexic group was identified with the use of partial and global report tasks, however the fMRI procedure included only a visual categorization task. In this task Latin letters were presented in pairs either with another letter (matched pairs) or with a geometrical figure (unmatched pairs). One of the stimuli was displayed in the center of the screen, and the other one was presented peripherally on the right or on the left side of the screen. The peripheral stimulus was either presented alone or closely flanked by two X letters. Participants were asked to look at the central stimuli and press a button when an unmatched pair was displayed. The flanked condition was designed as a much more demanding in terms of the attentional load than the isolated condition, and the brain activation of children was compared between these two conditions. The comparison revealed significantly lower activation of the left superior parietal lobule during the flanked condition in dyslexic children with a visual attention span deficit than in typically reading control group, but no group difference in the isolated condition (Peyrin et al., 2011).

Another study was performed on typically reading and dyslexic adults who presented a visual attention span deficit (Lobier et al., 2014). During fMRI procedure in this study, four types of stimuli were presented to the participants: letters, digits, Japanese Hirgana or pseudo-letters. The stimuli were either presented in sets of five elements (either of the same or of different type of stimuli, e.g. a string of letters and digits) or alone flanked by four hash signs (e.g. '# # 3 # #'). In the multiple element condition participants were asked to report the number of the stimuli of given category, and in the isolated condition they judged whether the central stimulus belonged to alphanumeric (letters and digits) or to non-alphanumeric (Hirgana and pseudo-letters) categories. The results of this study showed that dyslexic adults did not present higher activations of parietal areas for multiple element processing (more attentionally demanding than single element processing), although the increase of activation in parietal areas was observed in typical readers. The comparison of typical readers and adults with dyslexia revealed a significant reduction of the activity of the right superior parietal lobule in the dyslexic group, regardless of stimuli type (Lobier et al., 2014).

These two studies suggest that children and adults with dyslexia may present a hypoactivation of the superior parietal lobule during tasks which engage visual attention. However, the evidence is still limited, and there are no studies which would analyze the changes in the neural correlates of the visual attention span with time.

Chapter 3. Searching for dyslexia subtypes

The existence of different deficits in dyslexia leads to a question whether the group of children with dyslexia is hetero- or homogeneous. This question has been raised for almost 50 years (Boder, 1973), and despite accumulated knowledge it has not been entirely resolved. This Chapter presents the ideas on the subtypes of dyslexia based on visual and phonological processing, as well as the methods typically used to distinguish these subtypes.

Phonological and surface subtypes of dyslexia

The initial studies suggested that there are two distinct profiles of children with developmental dyslexia (Boder, 1973; Mitterer, 1982). These two profiles used to be established on the basis of reading of pseudowords and irregular words with correspondence to the dual-route model of reading (Coltheart et al., 1993; Saffran, 1985). According to this model, typical readers use two strategies when generating phonological output of reading aloud. The first strategy is so-called 'lexical' and the second one is 'sublexical'. The lexical strategy involves the orthographic representations of the words in the mental lexicon. As the mental lexicon stores only known words, this strategy cannot be used while reading pseudowords, which do not belong to the mental lexicon. The sublexical strategy is based on the correspondence between graphemes and phonemes, and may be used for pseudowords which match the language in terms of orthography (i.e. are readable in a way that they for example do not contain unpronounceable consonant clusters). According to this approach (developed originally for English), the two subtypes of dyslexia could be distinguished by a comparison of performance in reading regular pseudowords and irregular existing words. Children with 'surface' (lexical) dyslexia should be therefore relatively poorer in reading exception words (i.e. irregular existing words) than in reading regular pseudowords, and children with 'phonological' (sublexical) dyslexia should present the opposite pattern.

Although initially proposed over 30 years ago, this division is still present in literature on dyslexia subtypes (Birch, 2016; Kohnen et al., 2018; Sotiropoulos & Hanley, 2017). The existence of the two subtypes: a phonological and a non-phonological (surface), make it tempting to somehow connect these subtypes to the groups of dyslexic children with a phonological and a visual attention span deficit, and indeed such attempts have been done (Zoubrinetzky et al., 2014). In particular, a computer modelling study showed that a mild phonological deficit should result in difficulties in reading pseudowords (Harm & Seidenberg, 1999), and in fact severe phonological deficit was found in phonological dyslexics (Manis et al., 1996; Stanovich et al., 1997). Similarly, surface dyslexia can be related to the visual attention span deficit (Valdois et al., 2004). This connection was confirmed by a series of case studies of prototypical individuals with surface dyslexia who presented a visual attention span deficit (Bouvier-Chaverot et al., 2012; Dubois et al., 2010; Peyrin et al., 2012; Valdois et al., 2003) and by a recent study in which difficulties with visual processing were found only among children with surface, and not phonological dyslexia (Stefanac et al., 2019). On the other hand, some studies showed that both phonological and surface dyslexic children presented a phonological deficit as compared to typical readers (Jiménez et al., 2009).

Methods of finding dyslexia subtypes

There are several attempts how the deficits and subtypes in dyslexia may be defined. The most obvious method of finding children with the deficits is to define an arbitrarily set performance threshold, for instance that children who scored lower than 1.65 SD below average of a control group have a phonological deficit (Ramus et al., 2003; White et al., 2006). This criterion may obviously differ between studies, and other authors used such cutoffs as 1 SD below mean (Araújo et al., 2010; Genard et al., 1998; Sprenger-Charolles et al., 2011), or 1 SD below median score (van Ermingen-Marbach et al., 2013). There are several disadvantages of this method: it relies on an arbitrarily set cutoff, does not take into account the severeness of the possible coexisting deficits in one subject, and depends on the performance of the control group.

Some recent studies applied clustering methods (Giofrè et al., 2019; Heim et al., 2008; Jednoróg et al., 2014), and found either three or two clusters of children with dyslexia. Importantly, each of these studies found at least one cluster of dyslexic individuals with a severe phonological deficit (more severe than in other clusters), and the two studies which employed visual attention tasks reported also clusters of children with deficits in visual attention (Giofrè et al., 2019; Heim et al., 2008). Although clustering methods could be a promising solution for search of dyslexia subtypes, the main issue with applying clustering is the relatively low replicability of the results, as the number of the selected clusters may arbitrarily defined by the authors (Breckenridge, 2000).

The majority of the studies on phonological and surface dyslexia applied the procedure called 'regression outlier procedure' (Genard et al., 1998; Ho et al., 2007; Jiménez et al., 2009; Manis et al., 1996; Peterson et al., 2013, 2014; Sprenger-Charolles et al., 2000, 2011; Ziegler et al., 2008) proposed initially in a study on varieties of dyslexia (Castles & Coltheart, 1993). In this procedure, pseudoword reading scores are plotted against irregular word reading scores (and the other way around) and the 90% confidence intervals around the regression line are determined on the basis of the results of the control group (Ziegler et al., 2008) matched either by age or by reading level. Individuals who are below the 90% confidence interval when scores in pseudoword reading are plotted against scores in irregular word reading are considered phonological dyslexics.

As illustrated in Figure 4, children whose scores are below 90% lower limit are those who scored worse in pseudoword reading than it was expected on the basis of their irregular word reading scores (as the typical scores in pseudoword reading expected on the basis of irregular word reading should fall between the two 90% confidence interval lines). These children therefore have specific difficulties in reading pseudowords (as compared to reading irregular words), and could be included in the group of children with phonological dyslexia. Surface dyslexics are defined are those who are below the 90% confidence interval when scores in irregular words reading are plotted against scores in pseudowords reading.

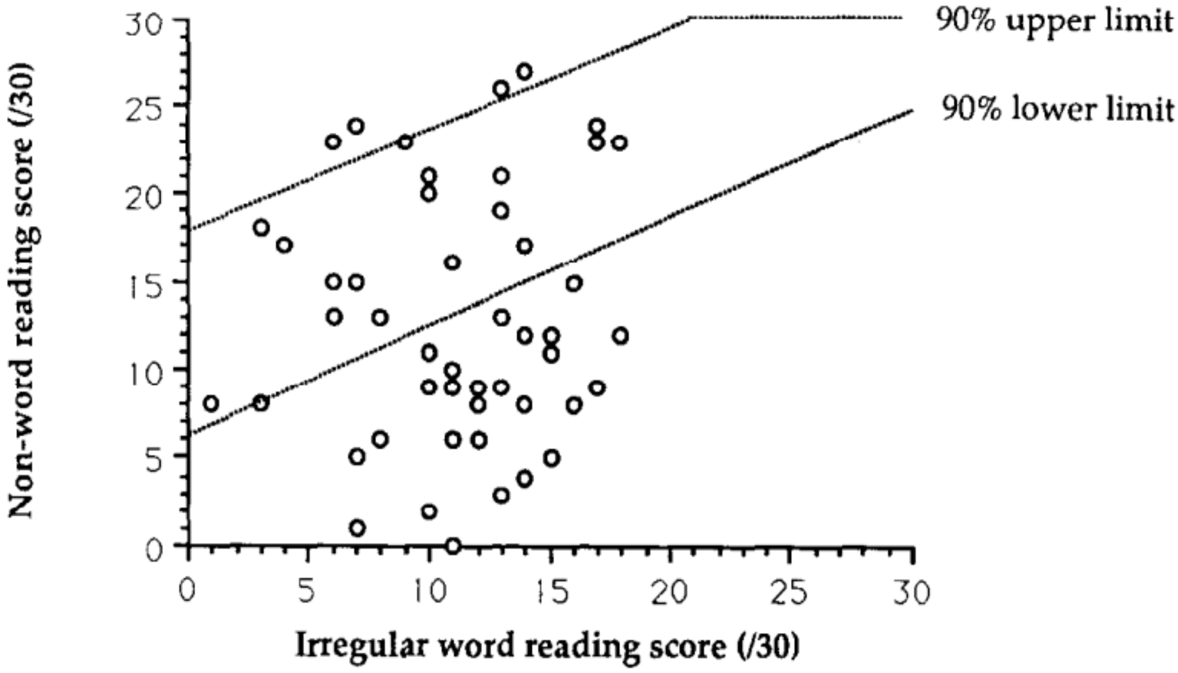

Figure 4. The picture of the 90% confidence intervals around regression line in a control group used for finding dyslexic participants with phonological dyslexia (Castles & Coltheart, 1993, p. 169).

Although the same method of searching for the surface and phonological deficits has been applied across many studies, the exact percentages of dyslexic children classified to either group differed dramatically between the studies, even in the same language. This method typically resulted in a higher rate of phonological (25–55%) than surface (27–30%) dyslexia in English (Castles & Coltheart, 1993; Manis et al., 1996; Sprenger-Charolles et al., 2011; Stanovich et al., 1997), and with a higher prevalence of the surface (29–59%) dyslexia than phonological one (4–17%) in French (Genard et al., 1998; Sprenger-Charolles et al., 2011;

Ziegler et al., 2008). However, the application of the regression outlier method to Spanish, a language with a transparent orthography, brought another pattern of results, as the vast majority of children with dyslexia presented no specific deficit (Sprenger-Charolles et al., 2011). In another study on Spanish the relative proportion of the two subtypes depended strongly on the control group: the surface dyslexia appeared to be more popular if the regression was based on the scores of an age-matched group, and the phonological dyslexia was dominant if a reading-level matched group was used (Jiménez et al., 2009).

Phonological and visual attention span deficits

Although widely used, the method described in the previous section cannot be applied in a study, which employs phonological and visual attention span tasks to reveal deficit groups. It is because the method requires two highly correlated measures (e.g. reading tests described above), where it is relatively easy to predict the score in one measure on the basis of the other one. Typically the visual attention span measured with a global or a partial report task is only slightly to moderately correlated with performance in phonological tasks (Banfi et al., 2018; Bosse et al., 2007; Germano et al., 2014; Saksida et al., 2016; Zoubrinetzky et al., 2014). In these studies the lowest obtained (not significant) correlation coefficient was -0.13 (for partial report of letters and phonological segmentation; (Zoubrinetzky et al., 2014) and the highest was 0.65 (for global letter report accuracy and spoonerism accuracy; (Saksida et al., 2016). The average of the 27 correlation coefficients between phonological and visual attention span tasks reported in these studies was 0.23, and the median was 0.20 (Banfi et al., 2018; Bosse et al., 2007; Germano et al., 2014; Saksida et al., 2016; Zoubrinetzky et al., 2014). Therefore another method of establishing deficits is needed if they are to be based on the performance in visual attention span and phonological tasks.

Such method was proposed in a study on French and English children with dyslexia (Bosse et al., 2007), and then replicated in subsequent French studies (Saksida et al., 2016; Zoubrinetzky et al., 2014), as well as in Brazilian Portuguese (Germano et al., 2014). In this method the principal component analysis is used to obtain a visual attention span factor and a phonological factor. Then dyslexic children who scored below the 10th percentile of the control group of the same age at either of the factors, are considered as being impaired on that factor.

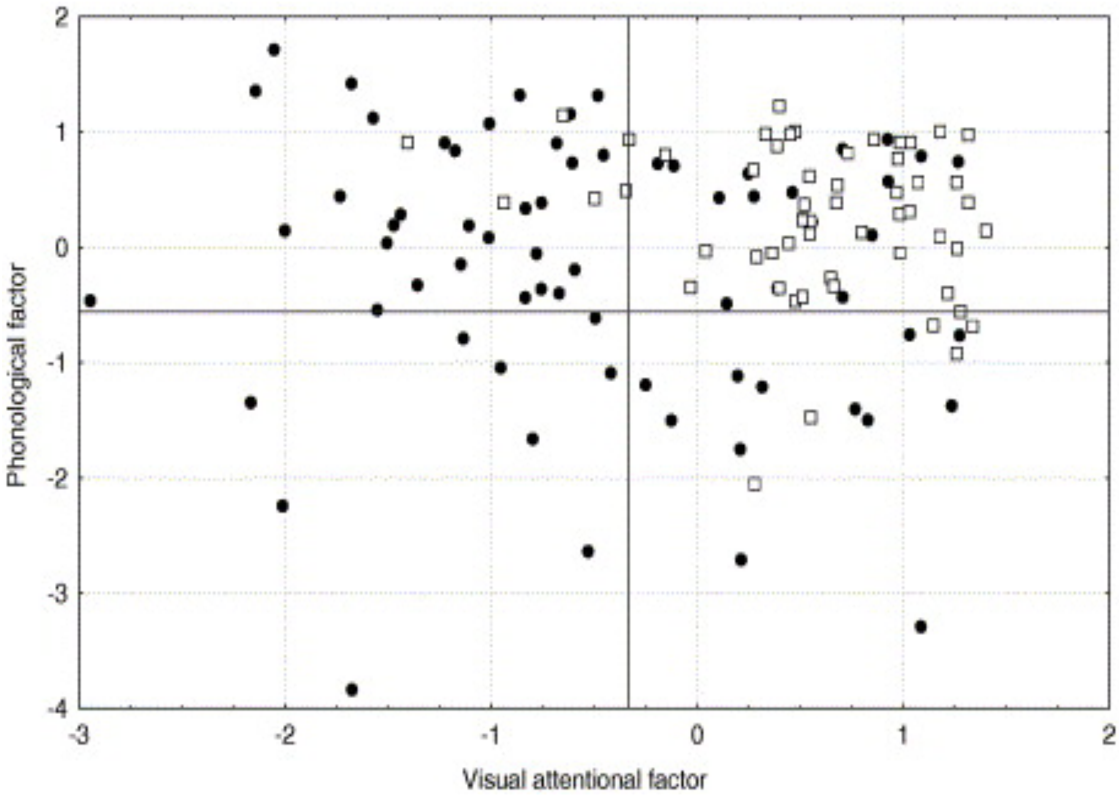

Figure 5. Visual attention span and phonological deficits in French children with dyslexia (black dots) as compared to typical readers (white squares; Bosse et al., 2007).

The division of the original sample is presented in Figure 5. The lines in the Figure correspond to the 10th percentile of the factorial scores in the control group, and therefore children who are below the horizontal line are considered to have a phonological deficit (as they have phonological scores as low as the lowest 10% of the control group), and children who are to the left of the vertical line are assumed to have a visual attention span deficit. Children who are both, below the horizontal and to the left to the vertical lines have both deficits, whereas children who are above the horizontal and to the right to the vertical line have no deficit.

Table 1. The frequency of phonological and visual attention span deficits across studies.

Study	Language	N (dyslexia)	Deficit			
			Phono.	**VAS**	**Both**	**None**
(Bosse et al., 2007)	French	68	19%	44%	15%	22%
	English	29	34.5%	34.5%	7%	24%
(Germano et al., 2014)	Brazilian Portuguese	33	15%	39%	33%	12%
(Zoubrinetzky et al., 2014)	French	71	32%	34%	17%	17%
Total		*201*	*25%*	*38%*	*18%*	*19%*

The prevalence of the deficits across the three studies which applied the same cutoff (10th percentile of the factorial scores in the control group) is presented in the Table 1. In general the previous studies showed a higher prevalence of visual attention span deficit (34–44%) than of phonological deficit (15–34.5%), and comparable percentages of children with both (7–33%) and none of the deficits (12–24%; (Bosse et al., 2007; Germano et al., 2014; Zoubrinetzky et al., 2014)). The two studies which also applied the principal component analysis on visual attention span and phonological scores, are not reported in the Table 1, as they either did not provide information about the prevalence of the deficits (Banfi et al., 2018), or applied another (-1.5 SD) cutoff which resulted in very high (over 97%) percentage of children with phonological deficit, though a very low (2%) percentage of children with an isolated visual attention span deficit (Saksida et al., 2016).

To summarize, searching for dyslexia subtypes with a deficit either in visual attention span or in phonological processing so far has brought relatively consistent results: the isolated phonological deficit has been found in about 15–35% of children with dyslexia, the isolated visual attention span deficit appeared in 34–44% of subjects, and the double deficit has been observed in 7–33% of people. However, these studies were done on opaque orthographies mostly (French and English) and much less is known about the prevalence of the two deficits in a transparent language. The earlier studies on the surface and phonological subtypes of dyslexia may suggest that this method could bring another pattern of results in a transparent orthography, as it had happened in the case of Spanish. On the other hand, the results from Brazilian Portuguese show higher percentage of the double deficit than found previously in English and French and a lower ratio of the isolated phonological deficit.

Stability of the deficits over time

As reviewed in Chapter 2, the time-stability of the phonological deficit among people with dyslexia may depend on the transparency of the orthography (Furnes & Samuelsson, 2011; Landerl & Wimmer, 2000; Wimmer, 1996), and seems to be higher in opaque than in transparent orthographies. On the other hand, research shows that if the applied task is demanding enough, the phonological deficit in readers with dyslexia may be stable over time not only in opaque (Johnson et al., 1999; Manis et al., 1993; Ozernov-Palchik et al., 2017), but also in transparent languages (Svensson & Jacobson, 2006).

Much less is known about the time stability of the visual attention span deficit. So far only one study examined the stability of visual attention span and its relation with reading over time (van den Boer & de Jong, 2018). In the longitudinal design, the authors assessed the visual attention span, phonological awareness and rapid automatized naming in 131 third graders who were tested again one year later. The authors reported a high correlation between the visual attention span skills measured in the third and in the fourth grade (with the use of global report task).

Finally, one should keep in mind though that the level of the visual attention span or phonological skills may be relatively stable over time, this stability does not necessarily mean that the division into subtypes would be also stable. The only study which longitudinally assessed the stability of the phonological and surface dyslexia (Peterson et al., 2014) found that the classification to the phonological subtype of dyslexia was more stable over time than membership in the surface dyslexia group, which could not be predicted from one time point to another. The group classified as the phonological subtype at the age of 8-13 years still presented poor phonological awareness skills 5 years later (on the group level), and 82% of the members of this group would be classified again as the phonological subtype. However, the group which had been assessed as having surface dyslexia at the first time point, did not present a distinct cognitive profile in the second measurement, and only 40% of children who initially presented a surface dyslexia would be classified to this group 5 years later.

So far there is no research on the time stability of the phonological and visual attention span subtypes of dyslexia, established based on task performance. As the phonological deficit in dyslexia has been shown to be relatively stable over time (especially in opaque languages) and the only study on the time stability of visual attention span also brought promising results, we could expect the two deficits to be persistent at least to some extent. On the other hand, the time-persistence of the visual attention span deficit in a transparent orthography has not been studied before and there is some evidence that in shallow orthographies phonological deficit may diminish over time.

Chapter 4. Phonological and visual attention interventions in dyslexia

Fluent reading demands both efficient phonological processing, and sufficient visual attention span, as described in Chapters 1 and 2. As dyslexic readers present deficits in these functions, it is intuitive to make an attempt to treat impaired reading by improving the underlying deficits. This Chapter describes the existing research that proved both phonological and visual attention trainings to be efficient in improving reading (under certain conditions). The trainings presented in the first part of current Chapter, although shown to be effective, are time-consuming and expensive. Therefore the last section of Chapter is devoted to an ad-hoc method of improving reading in children with dyslexia by modifying the properties of the texts.

Phonological trainings

The associations between phonological awareness and reading skills described in Chapter 1 may suggest that a training of phonological skills could lead to an improvement of reading performance. Indeed, efficiency of phonological trainings was confirmed by two meta-analyses (Bus & van IJzendoorn, 1999; Ehri et al., 2001) already two decades ago. The first meta-analysis included 38 experimental studies with more than 1900 participants (Bus & van IJzendoorn, 1999), performed in both the USA and in Europe. This meta-analysis showed that trainings of phonological awareness improve not only phonological skills but also - to a smaller extent - reading skills. This finding was confirmed also by the second meta-analysis of 52 studies (Ehri et al., 2001), which additionally showed that trainings of phonemic awareness increase not only fluency of reading but also the level of comprehension of the read texts, though have no impact on spelling skills. The effects of trainings based on phonological awareness were also visible a year after the interventions, as revealed by a recent meta-analysis of 71 studies (Suggate, 2016). However, these long-term effects were substantially smaller than the short-term effects (Bus & van IJzendoorn, 1999; Ehri et al., 2001; Suggate, 2010, 2016).

The meta-analyses underlined some factors which could make the phonological awareness trainings particularly efficient. First of all, both papers showed that trainings based on pure phonological awareness are less effective than trainings, which combine phonological processing and learning of letters (Bus & van IJzendoorn, 1999; Ehri et al., 2001). The authors argue that the application of some training of letter knowledge gives the participants some opportunities to use the acquired phonological skills on additional material. Moreover, the second meta-analysis found that the trainings were particularly effective when one or two phonological skills were trained instead of training a set of multiple phonological skills (Ehri et al., 2001).

The phonological awareness trainings were found to be of the most efficiency in preschoolers, while children form primary school can benefit less from phonological trainings (Bus & van IJzendoorn, 1999). This result was supported by a further meta-analysis of 85 intervention studies aimed at improving reading (Suggate, 2010), which showed that trainings based on phonological awareness are particularly effective until first grade, whereas in older students interventions aimed at training reading comprehension are more effective. However, the same study showed that trainings of phonological awareness continue to be effective also in middle grades of primary school (Suggate, 2010).

The above-mentioned meta-analyses did not analyse the effect of the language transparency on the effectiveness of intervention, although some of them included a wide range of languages, such as Danish, Dutch, Finnish, German, Hebrew, Norwegian, Spanish and Swedish in addition to English (Ehri et al., 2001). One of the meta-analyses did not mention the language of the participants of included studies (Bus & van IJzendoorn, 1999), and all other divided the languages into English and non-English (Ehri et al., 2001; Suggate, 2010, 2016). The found effects either did not differ between English and other languages (taken together; Suggate, 2010), or the interventions were more efficient in English than in non-English languages (Ehri et al., 2001). This study also reported that the transfer of improvement in phonological skills to reading was higher in English than in other languages (Ehri et al., 2001). The authors briefly connected this cross-linguistic difference to the low transparency of English, as compared to the majority of other languages included in the analyses, saying that phonological awareness training in an opaque orthography may make a bigger contribution to clarifying the idea of phonemes and their linkage to graphemes. However, the efficiency of the phonological interventions across various orthographies has not been studied systematically.

Visual attention trainings

The visual attention skills may be addressed in an intervention based on computer games (Antzaka et al., 2017; Franceschini et al., 2013, 2017). In the intervention studies which aimed at improving visual attention skills (and to transfer this improvement to reading skills), participants with dyslexia played computer games with high attentional requirements (action video games, AVG) and their progress in reading was compared to that made by peers who played non-action video games (NAVG). The specific features of the AVG include extraordinary speed (in terms of very rapid events and very high velocity of the moving objects), a high degree of perceptual, cognitive and motor load in the service of motor planning (i.e. multiple objects which need to be followed, multiple action places which must be considered and quickly performed), unpredictability (both spatial and temporal) and emphasis on peripheral processing (Franceschini et al., 2015; Green et al., 2010). These features make playing AVG demanding in terms of the load of visual attention, and therefore playing AVG may enhance the visual attention skills which are engaged during the training (Antzaka et al., 2017), as well as generalised visuo-attentional skills beyond the trained tasks (Green & Bavelier, 2003; Li et al., 2009; West et al., 2008). On the other hand, NAVG are defined as games of low visual attention load, and there are no reasons why playing NAVG should affect visual attention or reading skills.

The research on the impact of visual attention training, i.e. interventions based on AVG, is still limited. However, the existing studies quite consistently showed that players of the AVG enhanced visual attention and therefore improved their reading skills, though similar increase of reading level was not observed in the group which played NAVG (Franceschini et al., 2013, 2017). In particular, in the two studies Italian (*N* = 20) or English (*N* = 28) children with dyslexia played either AVG or NAVG for twelve hours in total. The analyses revealed that the group which played AVG improved both the reading speed and reading accuracy whereas no progress was observed in the NAVG players (Franceschini et al., 2013, 2017). What was even less expected, the AVG training resulted in increase of visuo-spatial attention, attentional shifting, as well as phonological short-term memory and phoneme blending skills (Franceschini et al., 2017), or in enhancement of focused and distributed attention (Franceschini et al., 2013), whereas NAVG did not affect these domains. These results were confirmed with a recent systematic review of five studies which used AVG and NAVG in participants with dyslexia (Peters et al., 2019).

However, the research on the efficiency of AVG interventions in children with dyslexia is far from flawless. First of all, the studies were performed on a very small groups and therefore could be seriously underpowered (Tressoldi et al., 2013). What is more, the progress in reading was not compared to a control group which played no games, and in fact it is not clear to what extent the enhancement of reading resulted from playing AVG, and not regular reading development.

Possible ad-hoc solution: Increase of inter-letter spaces

Although it is impossible to change the phonological properties of a language and to reduce the phonological difficulties of dyslexic readers in this way, it is relatively easy to modify the visual characteristics of the texts. The limitations of the visual attention span in people with dyslexia often coexist with difficulties with visual crowding (Lallier, Abu Mallouh, et al., 2018), and dyslexic children are particularly prone to visual crowding effects (Bertoni et al., 2019; Gori & Facoetti, 2015). Visual crowding describes difficulties in recognizing a stimulus surrounded by other similar stimuli, such as a letter or a word surrounded by other letters or words (Bernard & Castet, 2019). In visual attention span tasks, the visual crowding effects are observed when the smaller spaces between the presented items lead to lower performance (Lobier et al., 2012) and recent studies showed that reducing visual crowding (by increasing the spaces between the items) could lead to better visual attention span scores (He & Legge, 2017). Therefore dyslexic readers may benefit from larger distances between letters and words.

Initial reports on the effects of increased inter-letter spaces brought very enthusiastic results: in the condition of increased inter-letter spaces dyslexic children on the fly improved both reading speed and accuracy (Zorzi et al., 2012). In this study children were presented with a text in two conditions: a regular one and with extra-large spaces between the letters and between the words (see Figure 6). This increase of the inter-letter spaces resulted in an immediate improvement of both reading speed and accuracy in French and Italian dyslexic readers.

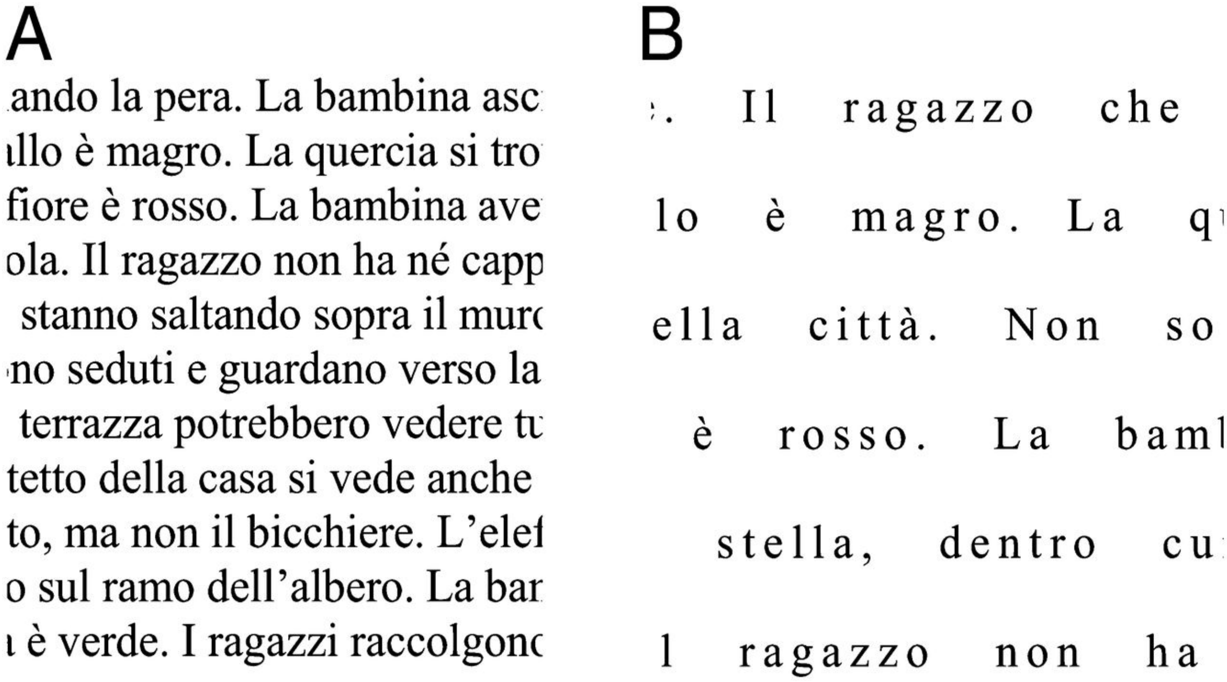

Figure 6. Samples of the texts read by the participants of the initial study on increasing inter-letter spaces in dyslexia (Zorzi et al., 2012, p. 11456).

However, further research on the effects of extra-large inter-letter spacing brought mixed results. In some studies, increased inter-letter spaces improved reading accuracy in subjects with dyslexia only (Bertoni et al., 2019; Dotan & Katzir, 2018; Duranovic et al., 2018; Sjoblom et al., 2016; Zorzi et al., 2012). In other research the increase of reading accuracy was observed in both typical readers and participants with dyslexia (Hakvoort et al., 2017), or not observed in either group (Masulli et al., 2018). Also the increase of reading speed was either observed in dyslexic participants only (Perea et al., 2012), in both groups (Duranovic et al., 2018; Sjoblom et al., 2016; Zorzi et al., 2012), or was not reported in either group (Bertoni et al., 2019; Dotan & Katzir, 2018; Hakvoort et al., 2017; Masulli et al., 2018; Perea et al., 2016). It is not clear how the modification of the inter-letter spacing affects other areas of reading performance such as comprehension of the read text and eye movements.

So far, only three studies have assessed the effects of increased inter-letter spacing on text comprehension either in skilled adult readers (Perea et al., 2016; Slattery et al., 2016) or in typically reading and dyslexic children (Perea et al., 2012). The research showed that in skilled readers the level of comprehension is not affected by the inter-letter spacing (Perea et al., 2012, 2016; Slattery et al., 2016). Dyslexic children however presented higher level of comprehension in the spaced condition than in the regular one (Perea et al., 2012).

Eye movement measures (number of fixations, duration of fixations) have been only rarely analysed in studies on inter-letter spacing. Increased inter-letter spacing may result in shorter fixation durations in skilled adult readers (Perea et al., 2016; Slattery & Rayner, 2013) and in children regardless of dyslexia (Masulli et al., 2018). The studies reported either no effect of inter-letter spacing on the number of fixations (Perea et al., 2016), or increased number of fixations in the spaced condition (Slattery & Rayner, 2013).

To summarize, increased inter-letter spacing have been initially shown as a very effective method of improving reading accuracy and speed in children with dyslexia on the fly. However, the subsequent studies were inconsistent in terms of results, and currently it is not clear whether increasing spacing enhances reading performance, and, if so, to what extent.

Part II: Original studies

Chapter 5. Research rationale

The initial aim of the present thesis was to examine visual attention span and phonological deficits in Polish children with dyslexia, as well as the neural correlates of these two deficits. In particular, we planned to assess what are the distributions of the visual attention span and phonological deficits among children with dyslexia, and what is the persistence of the two deficits. Then we planned to compare the neural basis of the phonological processing and the visual attention between the typically developing readers and children with dyslexia. Finally, we aimed at assessing the efficiency of the interventions based on trainings of visual attention skills and of phonological abilities, as well as as the effects of the increased inter-letter spacing.

However, this initial aim has evolved due to the unexpected results of the Experiment 1 (Chapter 6). In particular, in Experiment 1 we searched for the visual attention span and phonological deficits in two samples of children: a relatively large sample of children with dyslexia and typical readers (Experiment 1a, N = 215), and a smaller sample of younger children who participated in a longitudinal study (Experiment 1b, N = 108). We applied the same method of finding the two deficits, as used previously in other languages (Bosse et al., 2007; Germano et al., 2014; Zoubrinetzky et al., 2014). On the basis of previous results, we expected to identify the phonological deficit in about 25% of children and the visual attention span deficit in another 30% of participants with dyslexia (see Table 1). However, the results of the Experiment 1 differed from the expectations: Though we found a persistent phonological deficit in a large subsample of children with dyslexia, the visual attention span deficit was rare (Experiment 1a) and unstable over time (Experiment 1b).

Therefore, in the fMRI procedure we decided to focus on the neural correlates of poor phonological processing (Experiment 2, Chapter 7) and its development, and not to include visual attention span in the study. As in the Experiment 1b we showed that difficulties in phonological awareness are already present in children at the beginnings of formal education and are stable over time, in the Experiment 2 we searched for the brain basis of phonological processing in children who developed dyslexia at two time points: at the initial stage of reading acquisition and after two years of education. Similar longitudinal studies exploring neural correlates of phonological processing have been so far done on typical readers only (Yu et al., 2018).

Despite the lack of visual attention span deficit in Polish children with dyslexia, we deepended the verification of the visual attention theory of dyslexia in two intervention experiments. In the first intervention study (Experiment 3, Chapter 8) we directly compared the efficiency of a training based on attentional video games and a training bases on phonological non-attentional video games. Previous studies on the effects of intervention which used AVG reported enhancements of reading in children with dyslexia (Franceschini et al., 2013, 2017), irrespective of underlying cognitive deficits, although the improvement of reading has been said to be mediated by improvement of visual attention skills. Our aim was to examine whether AVG or phonological NAVG may be efficient in children with dyslexia who have only marginal difficulties with visual attention span. We compared the efficiency of the training based on AVG to a training which addressed phonological awareness, as the effects of phonological interventions have been consistently confirmed in meta-analyses (Bus & van IJzendoorn, 1999; Ehri et al., 2001; Suggate, 2010, 2016).

Finally, we assessed the effects of the increased inter-letter spacing in improving reading of Polish children with dyslexia (Experiment 4, Chapter 9). The previous research on the impact of the increased inter-letter spacing reported that the improvement of reading in children with dyslexia resulted from a decrease of visual complexity of the read texts (Bertoni et al., 2019; Dotan & Katzir, 2018; Duranovic et al., 2018; Hakvoort et al., 2017; Sjoblom et al., 2016; Zorzi et al., 2012). We aimed to assess whether increase of the inter-letter spaces may improve reading also in children with dyslexia who do not show deficits in visual attention span.

Chapter 6. The (tale of) two deficits: Experiment 1

The Experiment 1 was meant to provide the foundations for subsequent analyses. In particular, in the Experiment 1 we planned to find the subsamples of children with dyslexia who either presented phonological or visual attention span deficits. In order to find the two subtypes of dyslexia, we followed the procedure applied previously in a groups of English, French and Brazilian Portuguese children (Bosse et al., 2007; Germano et al., 2014; Zoubrinetzky et al., 2014). The procedure included assessment of phonological and visual attention span skills among children with dyslexia and typical readers, establishing phonological and visual attention span factors on the basis of a principal component analysis, and searching for children with dyslexia who scored below 10^{th} percentile of typical readers' scores in either of factors, as this threshold was used in the previous studies and revealed a reasonable ratio of dyslexic children with both deficits (Bosse et al., 2007; Germano et al., 2014; Zoubrinetzky et al., 2014; see Table 1).

The Experiment 1 consisted of two parts Experiment 1a and 1b, which differed in the exact design. Namely, in Experiment 1a we included data from a relative large sample (N = 215) of children with dyslexia (n = 89) and typical readers (n = 126). This large sample size made it possible to calculate the ratios of children with dyslexia who presented the two deficits in more reliable way than it has been previously done for another transparent language (Brazilian Portuguese), based on only 33 participants with dyslexia (Germano et al., 2014),

In the Experiment 1b we analyzed longitudinal data from a smaller sample of children (N = 108) who participated in the study at the beginning of their formal education, and were either diagnosed with dyslexia or assessed as typical readers after two years of schooling. In the longitudinal sample, we assess the time stability of the two deficits. Such analyses have not been done so far for visual attention span and phonological deficits, and the studies on the phonological and surface subtypes of dyslexia suggested that the level of time stability may differ between two deficits (Peterson et al., 2014).

Research questions

The aim of the Experiment 1 was to assess the distribution of the phonological and visual attention span deficits among Polish children with dyslexia, and to examine the time stability of the two deficits, as well as to compare the level of phonological and visual attention span skills between the dyslexic and typical readers, and to estimate the impact of both factors on the reading performance.

The particular research questions asked in the Experiment 1 were as follows:

1. What is the ratio of children with phonological and with visual attention span deficit among Polish children with dyslexia (Experiment 1a)?
2. What is the time stability of the phonological and visual attention span deficits among Polish children with dyslexia (Experiment 1b)?
3. Do children with dyslexia differ from typical readers in phonological and visual attention span skills)?
4. To what extent the phonological and visual attention span skills are related to reading?

The first two questions had an exploratory nature, and we formulated no exact hypotheses. On the basis of previous studies we expected the ratios of the two deficits to be similar to those reported in other languages (Bosse et al., 2007; Germano et al., 2014; Zoubrinetzky et al., 2014; see Table 1) but no assumptions were made in regards to the time stability of the deficits. However, we expected that on the group level children with dyslexia would present lower phonological awareness skills and lower level of visual attention span, and we expected both phonological awareness and visual attention span to explain independently some variance of reading.

Experiment 1a

Method

Participants

Two hundred twenty eight children participated in the study: 92 children with dyslexia and 136 children without dyslexia symptoms. The group was involved in a broader study on the cognitive heterogeneity of dyslexia, approved by the University of Social Sciences and Humanities Ethical Committee. All the participants were recruited through schools (parental gatherings), project website or psychological-pedagogical counselling centres. The parents of the participants gave a written consent for participation in the study, and all children gave an oral consent.

All participants were right-handed monolingual speakers of Polish. None of them was born preterm (before 37 weeks of pregnancy) or had any history of neurological illnesses or brain damage. The participants had no symptoms of ADHD and autism.

For the purposes of the Experiment 1a, participants with missing data either in one of the phonological or in one of the visual attention tasks, were excluded from the analyses. The final sample included 215 children aged 8.17–12.79 (M = 10.18, Me = 10.11, SD = 1.00), 86 girls and 129 boys.

In order to divide the sample into subgroups of children with and without reading impairment, we applied a standardized battery of tests used for diagnosis of developmental dyslexia. Children selected as having a reading disorder (n = 89) fulfilled criteria given in the user manual for the implemented battery of tests (Bogdanowicz et al., 2009). Namely, they either presented low reading accuracy (i.e., they scored below the 4th sten, which corresponds to at least 1 SD below population mean or below 16th percentile in a single-word reading task), or slow reading speed (i.e. they scored low in at least two out of three tasks: pseudoword reading, text reading, reading with lexical decision). Typically reading group (*n* = 126) consisted of children who scored low in no more than one reading speed subtest. Children classified as dyslexic achieved low scores in 2.61 tests on average (*SD* = 0.91, [2.41; 2.81]). Children classified as typically reading scored low in 0.21 tests on average (*SD* = 0.41, [0.15; 0.27]).

Groups of typical readers and children with dyslexia did not differ in sex, school grade, age, maternal or paternal education (measured in years of education) or socioeconomic status (measured on the basis of the Barratt Simplified Measure of Social Status, BSMSS; Barratt, 2006). However, the two groups differed slightly (small effect size) in nonverbal intelligence, which was higher in the typically reading group than in the group with dyslexia (Table 2).

Table 2. Typical readers and children with dyslexia in Experiment 1a.

	Typical Readers (n = 126)	**Dyslexic Readers (n = 89)**	
Sex	Female: 57 Male: 69	Female: 29 Male: 60	$Chi^2(1) = 2.97$, $p = .08$
School grade	3rd grade: 44, 4th grade: 43 5th grade: 39	3rd grade: 41, 4th grade: 25 5th grade: 23	$Chi^2(2) = 2.72$, $p = .26$
Age (years)	10.19 (0.97) [10.02; 10.37]	10.17 (1.05) [9.96; 10.39]	$t(213) = 0.15$, $p = .88$, $d = 0.02$
Socioeconomic status	104.60 (20.22) [101.01; 108.19]	99.55 (22.25) [94.92; 104.18]	$t(209) = 1.72$, $p = .09$, $d = 0.24$
Maternal education	17.30 (2.71) [16.81; 17.79]	17.05 (3.09) [16.40; 17.70]	$t(207) = 0.62$, $p = .54$, $d = 0.09$
Paternal education	16.63 (2.86) [16.12; 17.14]	16.31 (3.51) [15.59; 17.03]	$t(204) = 0.72$, $p = .47$, $d = 0.10$
Nonverbal IQ	117.21 (13.20) [114.84; 119.58]	113.30 (12.35) [110.81; 115.79]	$t(208) = 2.20$, $p = .03$*, $d = 0.31$

Note: *** - $p < .001$, ** - $p < .01$, * - $p < .05$. Mean (SD) [95% CI].

Procedure

Participants took part in a comprehensive study on the cognitive heterogeneity of developmental dyslexia. The study involved dyslexia diagnosis, IQ assessment, measurement of attentional, auditory and phonological skills via computerized tasks and both functional and structural MRI.

The phonological skills were assessed with two tests which belong to the normalized battery for dyslexia diagnosis (Bogdanowicz et al., 2009), namely a phoneme deletion task and a set of phonological tasks done on pseudowords. In the phoneme deletion task, participants were asked to delete a given phoneme from the heard word (e.g. say 'banana' without 'b' or say 'shoulder' without 'd'). Two versions of the battery were applied: one for 3rd and beginning 4th graders and one for the late 4th and 5th graders (Bogdanowicz et al., 2009; Jaworowska et al., 2010). Both versions consisted of 23 items and either six (in the younger group) or seven (in the older group) training items. As the two versions differed slightly in the exact items (out of 23 items 16 were the same in the two versions), instead of raw scores, we used the standardized (sten) scores.

The second phonological task, named Unknown Language (Bogdanowicz et al., 2009), included seven subtasks performed on pseudoword stimuli: paronym analysis (25 items), syllable analysis (5 items), syllable synthesis (5 items), phoneme analysis (8 items), phoneme synthesis (8 items), and phonological memory (4 items). In the first subtask, participants were asked to assess whether the two heard words were the same (e.g. 'mlak - mlak') or different (e.g. 'arte - alte'), and which phonemes differentiate the two words (e.g. 'r and l'). The subsequent subtasks included either synthesis, in which children were asked to synthesise a word from given syllables (e.g. 'fa-ma-da' to 'famada') or phonemes (e.g. 'z-o-r-a' to 'zora'), or analysis, in which children were asked to divide the words into syllables (e.g. 'kowa' to 'ko-wa') or phonemes (e.g. 'pakor' to 'p-a-k-o-r'). The final phonological memory subtask included pseudoword strings of growing length from three to six pseudowords. The children were asked to repeat as many pseudowords as they remembered immediately after hearing the whole string. The raw score was calculated as the sum of the scores in all subtasks. Then the raw score was transformed to a standardized (sten) score.

Visual attention span was assessed with two tasks typically employed in measurement of visual attention span abilities, i.e. global and partial reports. These tasks resembled the ones used in previous studies (Bosse et al., 2007; Germano et al., 2014; Saksida et al., 2016; Zoubrinetzky et al., 2014). The main difference was that instead of letters, we used nonverbal stimuli. For the global and partial symbol report task, quasi-random strings of four symbols were built up from eight symbols of similar visual complexity (Figure 7A). The global report task included 16 four-symbol strings, preceded by five training trails with feedback provided. The strings contained no repeated symbols. The symbols were presented in white on blue background (Figure 7B). Each symbol was used eight times and appeared twice in each position. At the beginning of each trial, a blank screen was presented for 1000 ms, followed by a central fixation cross presented for 150 ms. Then a symbol-string was displayed at the center of the screen for 500 ms, followed by a mask of four schematic snowflakes (Figure 7C) presented for 150 ms. In the global report task, children had to report by mouse-clicking as many symbols (from the presented string) as possible immediately after the string disappeared, by selecting symbols from the panel (Figure 7A). The score of the global report task was the number of accurately reported symbols (in terms of identity) across the 16 experimental trials, therefore maximal score equaled 64.

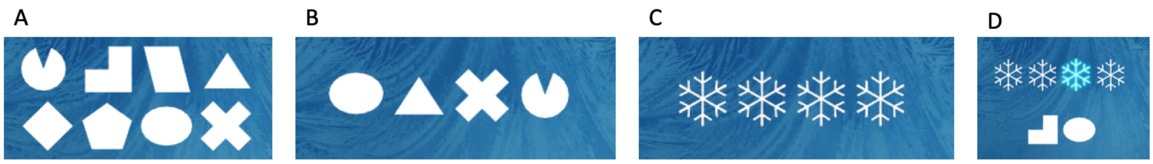

Figure 7. The symbols used in the visual attention span tasks in Experiment 1a.

In the partial report task, 32 four-symbol strings were presented, followed by the mask, similarly, as in the global report task. However, one of the snowflakes presented after the symbol-string was bolded (Figure 7D), and children were asked to select between the two symbols presented below the snowflakes. Participants' task was to choose the symbol presented previously on the bolded position. The experimental trials were preceded by five training trails. In the training trials participants were given feedback, and no feedback was given in the experimental trials. The score of the partial report task was the number of accurately selected symbols across the 32 experimental trials, with the maximum score of 32 points.

Word and pseudoword reading were additionally assessed with a task not included in the battery of tests applied for diagnosis of dyslexia (Szczerbiński & Pelc-Pękala, 2013). The task included two lists of real words and two lists of pseudowords of growing length. For each of the four lists participants were asked to read orally as many words as they could in 30 seconds. The number of correctly read items from the two lists were the summed up and used as an independent reading measure in the regression analyses.

Statistical analyses

The analyses were performed using R (R Core Team, 2019) with the use of the 'psych' (Revelle, 2019) and 'effsize' (Torchiano, 2020) packages. The R scripts used for the analyses are presented in the Appendix 1.

First, in order to reduce the redundancy in the data set, we run a principal component analysis with varimax rotation on the data from the two phonological and two visual attention span tasks, similarly as in previous studies (Banfi et al., 2018; Bosse et al., 2007; Germano et al., 2014; Saksida et al., 2016; Zoubrinetzky et al., 2014). In order to replicate the previous analyses

(Bosse et al., 2007; Germano et al., 2014; Zoubrinetzky et al., 2014), we used factor loadings greater than 0.70, and we set the number of expected factors to two.

Second, in order to explore the contribution of each factor to reading skills, we applied two hierarchical regression analyses with the two factors as independent variables and real word reading and pseudoword reading as dependent variables. Third, we compared the phonological and visual attention span skills between the typically reading children and children with developmental dyslexia with the use of two t-tests. Finally, we searched for children with dyslexia with specific difficulties either with phonological processing or with visual attention span. To achieve this aim, we followed the procedure used in previous studies (Bosse et al., 2007; Germano et al., 2014; Zoubrinetzky et al., 2014). Namely, we set a threshold for the cognitive disorder at the level of 10^{th} percentile of the scores in the typically reading group. Using this criterion we distinguished the two subgroups among the group with dyslexia.

Results

Principal component analysis

We obtained a two-factor solution with the first factors accounted for 39% of the variance and the second factor accounted for a further 32% of variance. The first factor was called phonological factor, as it received high loadings from the phoneme deletion (0.88) and the Unknown Language tasks (0.87). We labelled the second factor visual attention span factor, as it obtained loadings from the global report (0.82) and partial report tasks (0.78). The individual phonological and visual attention span factorial coefficients were then used as potential predictors of reading skills in the hierarchical regression analyses.

Hierarchical regression analyses

In order to explore the unique contribution of the phonological factor and the visual attention factor to reading of words and pseudowords, we carried out four hierarchical regressions. In all four models, we entered participants age at step 1. Then we entered either the phonological or the visual attention span factor at step 2, and added the other factor at step 3. Results of the hierarchical regression analyses are shown in Table 3.

The whole model based on age, phonological factor and visual attention span factor accounted for 22% of variance in word reading and for 18% of variance of pseudoword reading. The phonological factor contributed significantly to word and pseudoword reading and accounted for 14-15% of variance. However, the visual attention span factor either did not explain any additional variance, when added to the model after the phonological factor, or accounted for 1% of variance in reading, when added before the phonological factor.

Table 3. Results of hierarchical regressions in Experiment 1a.

	Adjusted R^2 change	
Factor	**Word reading**	**Pseudoword reading**
1. Age	.060***	.029**
2. Phonological	.148***	.142***
3. VA span	.009’	.009’
2. VA span	.011*	.011*
3. Phonological	.147***	.140***
Total R^2	.218***	.179***

Note: *** - p < .001, ** - p < .01, * - p < .05, ’ - p < .10

Comparison of the typical readers and children with dyslexia

In order to compare the phonological and visual attention span skills between the typically reading children and children with developmental dyslexia, we run two t-tests with either phonological or the visual attention span factor coefficients as the dependent variable. We found a large significant between-group difference in the phonological factor with typical readers (M = 0.37, SD = 0.90, [0.21; 0.53]) outperforming children with dyslexia (M = -0.52, SD = 0.90, [-0.72; -0.32]; $t(213) = 7.09$, $p < .001$, $d = 0.98$). However, we found no significant between-group difference in the visual attention span factor ($t(213) = 0.72$, $p = .47$, $d = 0.10$; typical readers: M = 0.04, SD = 0.99, [-0.14; 0.22]; children with dyslexia: M = -0.06, SD = 1.02, [-0.28; 0.16]).

Identification of the phonological and visual attention span deficits

In the next step, we explored whether different cognitive subtypes of dyslexia can be identified. For this purpose, we analyzed the distribution of the individual phonological factor and visual attention span factor coefficients derived from the principal components analysis. We followed previous studies (Bosse et al., 2007; Germano et al., 2014; Zoubrinetzky et al., 2014) and considered children whose score on one of the factors fell below the 10th percentile of the control group factorial score as having a particular deficit. The thresholds equaled -0.85 for the phonological factor, and -1.20 for the visual attention span factor

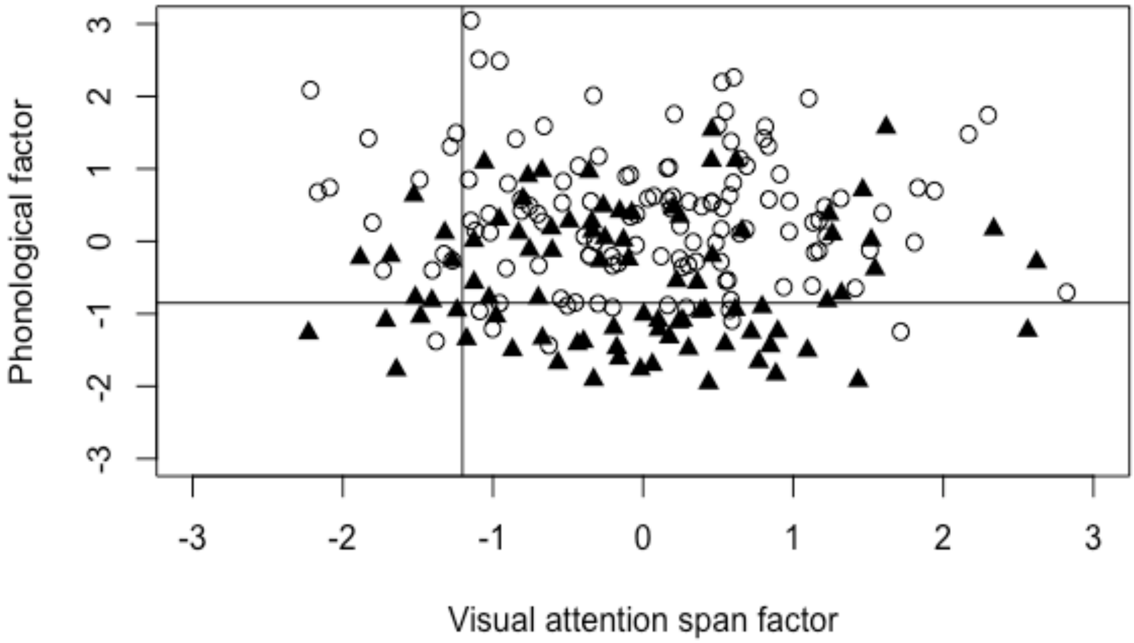

Figure 8. Scatterplots of the dyslexic (black triangles) and typically reading (white circles) participants according to their factorial coefficients. The vertical line corresponds to the 10th percentile of typical readers in the visual attention span factor, and the horizontal line corresponds to the 10th percentile of typical readers in phonological factor.

Figure 8 presents the scatterplot of the participants based on their phonological and visual attention span factorial coefficients. The two deficits were not represented equally. Indeed, 34 children with dyslexia (38%) showed a single phonological deficit, 7 children (8%) showed a single visual attention span deficit, and 5 (6%) showed a double deficit characterized by both poor phonological and visual attention span abilities. Remaining 43 children (48%) presented none of these two deficits.

Experiment 1b

Method

Participants

One hundred eight children participated in the study: 26 children with dyslexia and 82 children without dyslexia symptoms. The group was involved in a longitudinal study on the early predictors of dyslexia, approved by the Warsaw University Ethical Committee. The study consisted of three time points, a year apart from each other. All the participants were recruited through schools (parental gatherings) or the project website. Written consent was acquired from the parents of the participants, and all children gave an oral consent for participation in the study. All participants were right-handed monolingual speakers of Polish. None of them was born preterm (before 37 weeks of pregnancy) or had any history of neurological illnesses or brain damage. The participants had no symptoms of ADHD and autism.

For the purposes of the Experiment 1b, participants with missing data either in one of the phonological or in one of the visual attention tasks, either at the first or at the third time point, were excluded from the analyses. The sample included 105 children aged 5.52–8.06 (M = 6.86, Me = 6.80, SD = 0.55) at the first time point, and 7.60–10.06 (M = 8.83, Me = 8.77, SD = 0.56) at the third time point, 59 girls and 46 boys.

In order to divide the sample into subgroups of children with (n = 26) and without reading impairment (n = 79), at the third time point we applied a standardized battery of tests used for diagnosis of developmental dyslexia with the use of the same criteria as in the Experiment 1a. Children classified as dyslexic achieved low scores in 3.12 tests on average (SD = 0.71, [2.85; 3.39]). Children classified as typically reading scored low in 0.23 tests on average (SD = 0.43, [0.13; 0.33]).

Groups of typical readers and children with dyslexia did not differ in gender, school grade, age or nonverbal IQ (Table 4). They did however differ in terms of socioeconomic status (measured on the basis of the Barratt Simplified Measure of Social Status, BSMSS; Barratt, 2006), and in particular in terms of parental education: both maternal and paternal education was higher in the group of typically reading children than in the group of children with dyslexia, with a medium to large effect sizes.

Table 4. Typical readers and children with dyslexia in Experiment 1b.

	Typical Readers (*n* = 79)	**Dyslexic Readers (*n* = 26)**	
Sex	Female: 48 Male: 31	Female: 11 Male: 15	$Chi^2(1)= 2.01$, $p = .16$
School grade at TP1	1st grade: 58 kindergarten: 21	1st grade: 13 kindergarten: 13	$Chi^2(1) = 3.89$, $p = .05$
Age (years) at TP1	6.90 (0.55) [6.78; 7.02]	6.71 (0.57) [6.49; 6.93]	$t(103) = 1.55$, $p = .12$, $d = 0.35$
Age (years) at TP3	8.88 (0.55) [8.76; 9.00]	8.69 (0.56) [8.47; 8.91]	$t(103) = 1.51$, $p = .13$, $d = 0.34$
Socioeconomic status	98.35 (21.33) [93.65; 103.05]	79.44 (27.04) [69.05; 89.83]	$t(103) = 3.66$, $p < .001$***, $d = 0.83$
Maternal education	17.22 (2.83) [16.59; 17.85]	15.42 (4.01) [13.85; 16.99]	$t(102) = 2.49$, $p = .02$*, $d = 0.57$
Paternal education	16.22 (3.88) [15.36; 17.08]	12.80 (4.73) [10.94; 14.66]	$t(102) = 3.64$, $p < .001$***, $d = 0.84$
Nonverbal IQ	118.01 (11.01) [115.58; 120.44]	113.62 (11.90) [109.05; 118.19]	$t(103) = 1.73$, $p = .09$, $d = 0.39$

Note: *** - $p < .001$, ** - $p < .01$, * - $p < .05$ Mean (SD) [95% CI].

Procedure

Participants took part in a comprehensive study on the early predictors of developmental dyslexia. The study involved dyslexia diagnosis at the third time point, IQ assessment at the first and at the second time points, measurement of attentional, auditory and phonological skills via computerized tasks at all time points, and both functional and structural MRI at the first and at the third time point.

At each time point, the phonological skills were assessed with the same two tasks: phoneme analysis and phoneme deletion task (Szczerbiński & Pelc-Pękala, 2013). In the phoneme analysis task children were asked to divide the words into single phonemes (e.g. say 'o-k-o' after hearing the word 'oko'). The task included 12 real words of growing length, and children could score 1 point for each correctly divided item. The phoneme deletion task used 48 items and in the version applied in all three time points a time limit of 60 seconds was applied. At the third time point, additionally the phonological tasks used in the Experiment 1a were applied.

Visual attention span abilities at all three time points were assessed with two tasks of global and partial symbol reporting, similarly as in the Experiment 1a. The instructions for participants and the general design of the task, as well as the symbols used (Figure 9A) were the same as in the Experiment 1a. Similarly, we used strings of four symbols without repetitions (Figure 9B). The minor differences were that instead of white symbols on blue background we used grey stimuli on green background, and instead of snowflakes hash marks were presented (Figure 9C). The global report task included 20 four-symbol strings, preceded by five training trails, with a maximum score of 80 points.

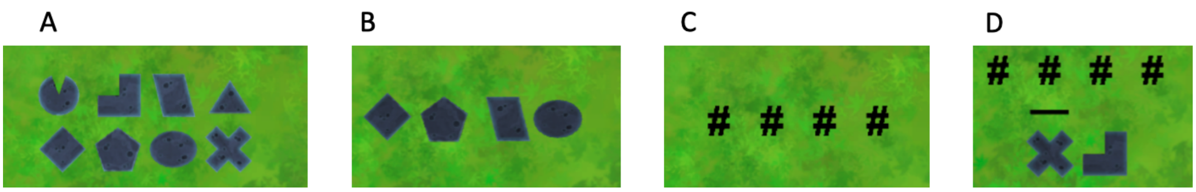

Figure 9. The symbols used in the visual attention span tasks in Experiment 1b.

In the partial report task, 40 four-symbol strings were presented, followed by the mask, similarly, as in the global report task. However, one of the hash marks presented after the symbol-string was underlined (Figure 9D), and children were asked to select between the two symbols presented below the hash marks. The experimental trials were preceded by 5 training trails. The score of the partial report task was the number of accurately selected symbols across the 40 experimental trials. Word and pseudoword reading was assessed with the same tasks as in the Experiment 1a (Szczerbiński & Pelc-Pękala, 2013).

Statistical analyses

The analyses were performed in the R (R Core Team, 2019) with the use of the ‘psych’ (Revelle, 2019) and ‘effsize’ (Torchiano, 2020) packages. The R scripts used for the analyses are presented in the Appendix 1.

Similarly as in Experiment 1a, we first run two principal component analyses, separately for the first and the third time point. For the first time point, we used the phoneme analysis and the phoneme deletion task as the measures of the phonological skills. For the third time point, we included the same tests as in the Experiment 1a, i.e. Phoneme Deletion and Unknown Language tests. For both principal component analyses, we used the scores of the global and of the partial report tasks as the measures of the visual attention span. In both analyses, we set the number of factors to two. Second, in order to further explore the impact of the two factors on reading skills, we applied six hierarchical regression analyses. The analyses used the two factors as independent variables and either word reading or pseudoword reading as dependent variables, similarly as in the Experiment 1a. The hierarchical regression analyses were run separately for the first time point, and then for the third time point. Finally, we tried to predict reading skills at the third time point with the use of the two factors from the first time point.

Next, we repeated the between-group comparisons done in the experiment 1a with the use of a series of t-tests: we compared the phonological and the visual attention span factorial coefficients from the first and the third time point between the typical readers and children with dyslexia.

Then we applied the same criteria as in the Experiment 1a to search for children with the phonological and the visual attention span deficit. Namely, we set a threshold for the cognitive disorder at the level of 10th percentile of the scores in the typically reading group at a given time point. Finally, we compared the subgroups of children with each of the deficits at first and at the third time point in order to explore the time stability of the two deficits.

Results

Principal component analyses

Based on the data from the first time point, we obtained a two-factor solution with the first factors accounted for 45% of the variance and the second factor accounted for a further 28% of variance. The first factor received high loadings from phoneme analysis (0.93) and phoneme deletion (0.89) and hereafter was called phonological factor. The second factor obtained high loadings from the partial report (0.89) and moderate loadings from the global report tasks (0.57) and therefore was labelled visual attention span factor.

Similarly, for the third time point, we obtained a two factor solution, with the first factor accounted for 42% and the second factor accounted for 34% of the variance. Again, the first, i.e. phonological, factor obtained high loadings from the phonological tasks, namely 0.86 from phoneme deletion and 0.93 from Unknown Language tasks, and the second, i.e. visual attention span, factor obtained high loadings from the global report (0.73) and partial report (0.86) tasks.

The individual phonological and visual attention span factorial coefficients from both time points were separately saved and then used as predictors of reading skills in the hierarchical regression analyses.

Hierarchical regression analyses

Similarly, as in the Experiment 1a, we carried out hierarchical regressions to explore the contribution of the phonological and visual attention span to the reading of words and pseudowords. We run three separate sets of models: the first one for the first time point, the second one for the third time point, and the third one, in which we tried to predict reading at the third time point on the basis of the factors from the first time point. In all sets of models, the participants' age was entered at the step 1, either phonological or visual attention span factor at the step 2, and the other factor at the step 3 (see Table 5).

Table 5. Results of hierarchical regressions in Experiment 1b.

	Adjusted R^2 change					
	TP1		**TP3**		**TP1 to TP3**	
Factor	**RW**	**PW**	**RW**	**PW**	**RW**	**PW**
1. Age	.117***	.159***	.028*	.014	.035*	.019’
2. Phonological	.522***	.544***	.330***	.304***	.318***	.191***
3. VA span	.000	.000	.036**	.066***	.006	.032*
2. VA span	.000	.000	.029*	.058*	.000	.011
3. Phonological	.522***	.544***	.337***	.312***	.323***	.213***
Total R^2	.639***	.703***	.395***	.384***	.358***	.242***

Note: *** - $p < .001$, ** - $p < .01$, * - $p < .05$, ‘ - $p < .10$.
RW - real words reading, PW - pseudowords reading, TP - time point.
TP1 to TP3: predictors from the first time point used to predict the reading at the third time point.

At the first time point, the models accounted for 64–70% of variance of reading. The phonological factor at the first time point contributed to both reading of words and pseudowords and accounted for 52–54% of variance, though the visual attention span was not a significant predictor of reading skills. At the third time point, 38–40% of variance could be explained by the models. The phonological factor accounted for 30–34% of variance, and the visual attention span factor accounted for additional 3–7% of variance. Finally, the model based on the phonological and visual attention span factors from the first time point accounted for 24–36% of variance in reading at the third time point. In particular, phonological factor accounted for 19–32% of variance. However, the visual attention span factor either did not explain any additional variance, or accounted for only 3% of variance.

Comparison of the typical readers and children with dyslexia

In order to compare the phonological and visual attention span skills between the typically reading children and children with developmental dyslexia, we run two t-tests with either phonological or the visual attention span factor coefficients as the dependent variable. At both time points typical readers scored higher in the phonological factor than children with developmental dyslexia (Table 6), and the observed difference were large. However, we found no significant between-group difference in the visual attention span.

Identification of the phonological and visual attention span deficits

Finally, we analyzed the distribution of the individual phonological factor and visual attention span factor coefficients derived from the principal components analysis. We defined the deficits in the same way, as in the Experiment 1a, i.e. by setting the threshold to the 10^{th} percentile of the particular factor in the control group. The exact values of the obtained thresholds were: -1.07 for the phonological and -1.16 for the visual attention span factors at the first time point, and -0.93 for the phonological and -1.24 for the visual attention span at the third time point.

Table 6. Phonological and visual attention span factor scores in typical readers and children with dyslexia in Experiment 1b.

	Typical Readers (n = 79)	**Dyslexic Readers (n = 26)**	
Phonological factor TP1	0.24 (0.98) [0.02; 0.46]	-0.73 (0.65) [-0.99; -0.48]	$t(103) = 4.71$, $p < .001$***, $d = 1.06$
Visual attention factor TP1	0.07 (0.98) [-0.15; 0.29]	-0.22 (1.04) [-0.61; 0.17]	$t(103) = 1.30$, $p = .20$, $d = 0.29$
Phonological factor TP3	0.27 (0.87) [0.07; 0.47]	-0.82 (0.92) [-1.17; -0.47]	$t(103) = 5.46$ $p < .001$***, $d = 1.23$
Visual attention factor TP3	0.11 (0.93) [-0.09; 0.31]	-0.33 (1.14) [-0.76; 0.10]	$t(103) = 1.97$, $p = .05$, $d = 0.45$

Note: *** - $p < .001$, ** - $p < .01$, * - $p < .05$ Mean (SD) [95% CI].

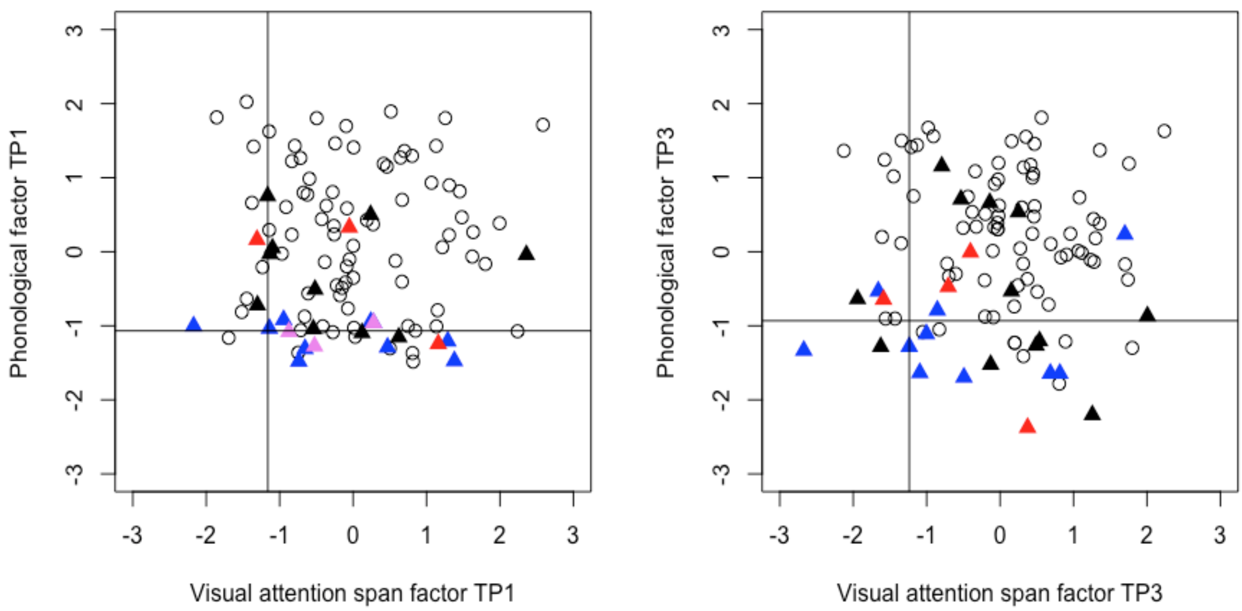

Figure 10. Scatterplots of the dyslexic (triangles) and typically reading (circles) participants according to their factorial coefficients at the first and at the third time points. The colors of the triangles correspond to the deficit presented at the other time point: phonological (blue), visual attention span (red), double (violet) or none (black), e.g. children marked with blue at the left panel (TP1) presented a phonological deficit at TP3 (right panel).

The colors of the triangles on the Figure 10 correspond to the deficit of the participants at the other time point, i.e. children marked with blue at the left panel presented a phonological deficit at the third time point, and children marked with blue at the right panel showed a phonological deficit at the first time point. Similarly, children marked with red at the left panel presented a visual attention span deficit at the third time point, and children marked with red at the right panel had this deficit at the first time point. If the deficits are time-stable, the blue triangles should be placed low at the scatterplot, i.e. children who had a phonological deficit at the other time point should score low on the phonological factor, and the red triangles should be placed at the left side of the plot, i.e. children who showed a visual attention span deficit at the other time point should score low on the visual attention span factor. The violet triangles at the left panel represent children who presented a double deficit at the third time point.

The distribution of the blue triangles suggests a high time stability of the phonological deficit: 70% of children who presented a phonological deficit at the first time point, presented the same deficit at the third time point (see also Table 7), and 50% of the children who showed a phonological deficit at the third time point had this deficit already at the first time point. The stability of the phonological deficit is visible also, while the factor is treated as continuum, not a dichotomous variable. In particular, children who presented a phonological deficit at the first time point scored low on the phonological factor at the third time point (M = -1.14, Me = -1.31, SD = 0.62), and children who showed a phonological or double deficit at the third time point had already low phonological scores at the first time point (M = -1.16, Me = -1.12, SD = 0.22). The Pearson correlation coefficient between the two phonological factors suggests a moderate to strong positive relation ($r(103) = .62$, $p < .001$).

Table 7. The distribution of the phonological, visual attention span (VAS), and double deficits in children with dyslexia at the first and the third time points in Experiment 1b.

		Deficit at TP1			
		Phonological	**VAS**	**None**	***Sum***
Deficit at TP3	**Phonological**	5	1	4	*10*
	Double	2	0	1	*3*
	VAS	1	1	1	*3*
	None	2	2	6	*10*
	Sum	*10*	*4*	*12*	

However, just one child presented a visual attention span at both the first and the third time point (Table 7). Children who presented a visual attention span deficit at the first time point scored on average within typical ranges at the third time point (M = -0.58, Me = -0.56, SD = 0.81). Similarly, the scores on the visual attention span factor at the first time point of the children who presented a visual attention span or a double deficit at the third time, were within the limits of typical scores of the control group (M = -0.07, Me = -0.05, SD = 1.24). The Pearson correlation coefficient between the two visual attention span factors suggests a weak positive relation ($r(103) = .27$, $p = .006$).

Discussion

The goal of the experiments presented in this Chapter was to explore the phonological and the visual attention span deficits in Polish children with dyslexia. The results could be summarized as follows. First, Polish children with developmental dyslexia show deficit in phonological awareness. This deficit is present in 39–51% of children with dyslexia, and as a group children with dyslexia present much lower level of phonological awareness than their typically reading peers. Second, visual attention span deficit is very rare in Polish children with dyslexia, and it was observed in 14–24% of children (including children with double phonological and visual attention span deficits). Last, difficulties with phonological awareness are not only stable over time but also phonological skills are related to reading scores in children at first five classes of primary school.

Phonological deficit in Polish children with dyslexia

We found that Polish children with developmental dyslexia present, as a group, significantly lower phonological awareness than typical readers. The differences between groups were observed at both time points of the longitudinal study (when children were aged 5.5–8 years and 7.6–10 years respectively), as well as in the cross-sectional study on older children (aged

8.1–12.8 years). The effect sizes of all differences were large (Cohen's $d > 0.9$), and similar in both experiments. This outcome confirms the previous reports about Polish children with dyslexia, which found deficient phonological skills (Krasowicz-Kupis et al., 2009; Lipowska et al., 2008). The similar (large) size of the differences between the children with dyslexia and typical readers also replicates previous studies on transparent languages, showing that when the phonological tasks are demanding enough, the difficulties with phonological awareness may be observed in dyslexic children at various ages (de Jong & van der Leij, 2003).

On the other hand, the hierarchical regression analyses revealed that the relation between the phonological skills and reading scores was the highest in the youngest group, as in the first time point of the longitudinal study phonological factor explained 64–70% of variance in reading. After two years of education, the ratio of variance explained by phonological skills was substantially smaller, though still relatively high (38–40%). Whereas in the oldest group in Experiment 1a phonological skills accounted for only 14–15% of variance in reading. This decrease in the predictive power of phonological skills may be related to the decreasing with age impact of phonological awareness on reading reported in transparent languages (Landerl & Wimmer, 2000; Wimmer, 1996).

Phonological deficit, as defined in previous studies (Bosse et al., 2007; Germano et al., 2014; Zoubrinetzky et al., 2014) was found in 39–51% of Polish children with dyslexia, and 38–39% of children with reading impairment presented isolated phonological deficits with no deficit in visual attention span. These ratios are lower than in a study on Polish adults (Reid et al., 2007), which found an isolated phonological deficit in 60% of participants, but the differences may result from various definitions of the deficit. The previous studies which employed the same definition of the deficits found the isolated phonological deficit in 15–34.5% of participants with dyslexia (see Table 1), and the double deficits in additional 7–33% of dyslexics. In total, the ratios of participants who presented phonological deficit (either isolated or together with visual attention span deficit) differed between 34% in English (Bosse et al., 2007) and 49% in French (Zoubrinetzky et al., 2014), and were very close to the percentage found in the current thesis. The similarities between the percentage of children with dyslexia who present low phonological skills across the four languages which used the same method (English, French, Brazilian Portuguese and Polish) may point at the universality of the phonological deficit in dyslexia (Ziegler & Goswami, 2005).

In the longitudinal study, the phonological deficit was found to be stable over time, as 70% of children who presented the deficit at the first time point were still classified as having a phonological deficit two years later, and in general the phonological abilities of the children who presented a phonological deficit in at least one time point were low at both time points. The high stability of the phonological deficit over time replicates the findings reported in a study on phonological and surface dyslexia (Peterson et al., 2014). That study reported a stable pattern of results in children with phonological (as compared to surface) dyslexia even five years after the first classification. The time stability of the deficit replicates also previous findings on high stability of the phonological abilities in Swedish, i.e. another language with transparent orthography (Svensson & Jacobson, 2006).

The lack of visual attention span deficit

The results on the visual attention span deficit are also very consistent but present an opposite pattern to what was found in case of the phonological deficit. First of all, visual attention span did not differentiate between typical and dyslexic readers in both studies: the differences in the visual attention span skills were not statistically significant and of marginal size. There could be several explanations of this lack of differences but the most intrusive refers to the type of stimuli used in the measurement of the visual attention span.

Since some of the participants were prereaders the global and partial report tasks applied in the current study were done on symbols (and not letters or digits) and the participants were asked to report the remembered stimuli by selecting the symbols on the screen and pressing mouse buttons (and not by naming the objects orally). The previous studies which showed differences in visual attention span between typical readers and children with dyslexia typically used letters or digits as stimuli reported orally (Bosse et al., 2007; Germano et al., 2014; Lallier et al., 2014; Lassus-Sangosse et al., 2008; Lobier et al., 2012; Valdois et al., 2012; Yeari et al., 2017; Zoubrinetzky et al., 2014). The studies in which nonverbal assessment methods were used showed no difference between dyslexic and typically reading adults (Hawelka & Wimmer, 2008; Shovman & Ahissar, 2006; Yeari et al., 2017) or children (Banfi et al., 2018), similarly as found in our results. Finally, some of the previous studies which employed both alphanumeric and other type of stimuli, reported an interaction between group and type of stimuli, as the between-group difference were found only when digits or letters were used, but not in case of colours (Valdois et al., 2012) or symbols (Collis et al., 2013; Ziegler et al., 2010). The lack of differences between typical readers and children with dyslexia when non-alphanumeric stimuli are used suggest that the limitation of the visual attention span in dyslexia may simply result from limited experience with alphanumeric stimuli, i.e. restricted reading experience. The specificity of the differences to the alphanumeric stimuli could be related to difficulties in processing and naming digits and letters as reported by studies on rapid automatized naming (McBride-Chang & Manis, 1996; Wolf et al., 1986). These studies showed that typical readers when acquiring reading, automatize naming of letters and digits, and this process of automatization is less efficient in children with dyslexia (McBride-Chang & Manis, 1996; Wolf et al., 1986). On the other hand, previous studies which found the selective visual attention span impairment with letter and digits claimed that this finding supports the phonological deficit theory of dyslexia (Ziegler et al., 2010), as alphanumeric stimuli, in contrast to symbols, can be easily mapped onto phonological code.

The visual attention span also did not explain a significant amount of variance in reading: the ratio of the explained variance differed between 0 and 7%, and visual attention span factor was a significant predictor of reading skills only at the third time point of the longitudinal study, i.e. when children were 7.6–10 years old. Finally, the deficit in visual attention span was observed in 14 to 24% of children with dyslexia, and the isolated visual attention span deficit was visible in 8 to 15% of participants. This percentages are just slightly higher than the ratio of typically reading children who presented the same level of visual attention span abilities (i.e. 10%), and much lower than in previous studies (Bosse et al., 2007; Germano et al., 2014; Zoubrinetzky et al., 2014). This low ratio of visual attention span deficit may again be explained by the applied tasks, and in particular the non-oral report of non-alphanumeric stimuli. However, the used method of measurement cannot explain the low time stability of the visual attention span. In particular, we found that children who presented a visual attention span deficit when attending kindergarten or first grade, presented typical scores on visual attention span factor two years later; and the other way around: children who had a deficit in visual attention span after two years of education, had had typical scores two years earlier. The weak correlation between the visual attention span factors measured at two time points (r = .27) is much lower than previously reported (van den Boer & de Jong, 2018). However, the previous longitudinal study not only used a shorter interval (one year as compared to two years in the current study) between the measurements, but also applied an oral global report of letters. The authors of the previous longitudinal study on visual attention span mention this choice of task as a limitation of their study (van den Boer & de Jong, 2018).

Perhaps, in the current study we could have identified more children as having a visual attention span deficit and we could have found higher time stability of the visual attention span factor, if we had applied alphanumeric version of the task. However, use of alphanumeric material, especially in the longitudinal experiment, was not possible as the participating children at the first time point were just beginning formal education and not all of them knew letters and digits.

To summarize, we found a phonological deficit in a significant ratio of children with dyslexia, independently from their age. The phonological skills were related to reading scores, and the deficit in phonology was stable over time. On the other hand, the visual attention span deficit was rare and unstable, and the visual attention span skills were not related to reading performance.

Chapter 7. Neural correlates of the phonological deficit: Experiment 2

The Experiment 2 aimed at finding the neural correlates of the phonological processing. As reviewed in the last section of Chapter 1, previous studies on the brain activation during phonological processing, which explored phonological awareness independently of reading, produced inconsistent results. These studies either show a hypoactivation of the left dorsolateral prefrontal cortex (Kovelman et al., 2012) or a broader hypoactivation of the left fusiform gyrus in children with dyslexia (Desroches et al., 2010). The number of studies which explored the neural correlates of phonological processing in children across various ages is limited: two such studies showed age-related increases of the brain activation in the left dorsal inferior frontal and temporal gyri (Brennan et al., 2013; Cone et al., 2008) and inferior parietal cortex (Brennan et al., 2013). The only longitudinal study which so far explored the development of the phonological network in typical readers, showed a decrease in activation of the left inferior parietal cortex and bilateral precenues (Yu et al., 2018). These studies however did not examine the development of the phonological network in children with dyslexia, and the Experiment 2 was aimed to close this gap in research.

The design and the results of the Experiment 2 were published in a broader context of the development of phonological and reading skills, as well as neural phonological network in children with and without familial risk of dyslexia (Łuniewska et al., 2019).

Research questions

The aim of the Experiment 2 was to explore longitudinally what changes in the neural correlates of phonological processing when children learn to read, and either become proficient readers or develop dyslexia. In the Experiment 2 we compared the brain activation during phonological processing in children with dyslexia and in typical readers at two time points: in the first grade or kindergarten and after two years of school education (similarly as in the Experiment 1b, as these two Experiments analyze data from the same project).

We expected typical readers to show reduced brain activation in the phonological processing network after two years of reading acquisition as compared with the early stage of education, in line with previous reports (Yu et al., 2018) and the Interactive Specialization Theory (Johnson, 2000, 2001, 2011). We hypothesized that children with dyslexia would present behavioral and brain activation alterations as compared to typical readers at both early and later stages of education. Namely, we expected children with dyslexia to show low accuracy in both reading and phonological assessments at all measurement points and to show hypoactivation of left hemisphere structures responsible for phonological processing, as was previously reported in case of poor readers (Desroches et al., 2010; Kovelman et al., 2012).

Method

Participants

The participants were a sample of the same group which took part in the Experiment 1b. The whole group included 108 children, and the group who completed the fMRI task in the first time point included 102 participants (Dębska et al., 2016). Nine of these children left the project due to losing interest in the study or moving to another city. Additionally, we excluded data from three children (the two youngest ones and the oldest one) to clearly separate the age ranges of subjects during the two time points.

The sample analyzed in the Experiment 2 included 90 children (53 girls and 37 boys) aged 5.94–7.95 years (M = 6.91, Me = 6.90, SD = 0.49) at the first time point, 6.99–9.43 (M = 7.88, Me = 7.87, SD = 0.50) at the second time point, and 8.05–10.05 years (M = 8.95, Me = 8.92, SD = 0.49) at the third time point. At the first time point, 27 children were attending kindergarten and 63 were attending first grade of primary school. Two years later the group consisted of 27 second graders and 63 third graders, as the children progressed in their education. There was also no difference in distribution to the school grades between children diagnosed later with dyslexia and typical readers.

As described in the Experiment 1b, the third time point included a formal diagnosis of dyslexia. The same criteria of classifying to dyslexic or typically reading group as described in the Experiment 1 were applied. In the group which participated in the Experiment 2, there were 20 children with dyslexia and 70 typical readers. There were no differences between the group with dyslexia and typical readers in terms of age, sex, grade, and IQ as measured with WISC-R. The parental SES, and performance IQ (measured with Raven Matrices) were slightly lower in the dyslexic group than in the typically reading children. However, these difference did not survive Bonferroni correction for multiple comparisons (see Table 8).

Procedure: Behavioural Measures

Participants completed three phases of behavioral tests which included measuring reading skills, letter knowledge, rapid naming, and phonological awareness (all time points), and language and cognitive skills (the first time point). In the current Chapter we only describe the tests relevant for the hypotheses of the Experiment 2, but a comprehensive list of the used tasks and the results of the both groups are described elsewhere (Łuniewska et al., 2019). We used the same test battery to measure letter knowledge, word and pseudo-word reading, phoneme deletion and phoneme analysis at each time point (Szczerbiński & Pelc-Pękala, 2013). Intelligence was measured with Raven's Colored Progressive Matrices (Szustrowa & Jaworowska, 2003) at the first time point, and with Wechsler Intelligence Scale for Children - Revised (Matczak et al., 2008) at the second time point. At the third time point, a standardized battery of tests for diagnosing dyslexia was used (Bogdanowicz et al., 2009). We compared the scores in behavioral tests between children with dyslexia and typical readers at all time points. Due to unequal sample sizes we applied non-parametric tests, and due to the high number of comparisons, we followed the analysis with Bonferroni corrections. The R script used for the visualization of the behavioral data is included in Appendix 2.

Table 8.Typical readers and children with dyslexia in Experiment 2.

	Typical readers (***n*** **= 70)**	**Dyslexic readers** (***n*** **= 20)**	
Sex	26 boys 44 girls	11 boys 9 girls	$Chi^2 = 2.05$ $p = .152$
Grade at TP1	52 first grade 18 kindergarten	11 first grade 9 kindergarten	$Chi^2 = 2.76$ $p = .097$
Age at TP1 & TP3 (years)	6.94 (0.49) [6.83; 7.05] 8.98 (0.50) [8.86; 9.10]	6.81 (0.46) [6.61; 7.01] 8.85 (0.46) [8.65; 9.05]	$F(1,88) = 0.94$; $p = .336$ $\eta_p^2 = .011$
Socioeconomic status	50.00 (9.97) [47.66; 52.34]	41.73 (13.35) [35.88; 47.58]	$U = 457$; $p = .018$; $d = 0.78$
Number of letters known at TP1 & TP2	51.36 (15.07) [47.83; 54.89] 63.04 (2.57) [62.44; 63.64]	30.50 (19.53) [21.94; 39.06] 58.90 (8.84) [55.03; 62.77]	$F(1,88) = 28.37$, $p < .001$* $\eta_p^2 = .244$
Raven Matrices IQ (sten)	7.70 (1.16) [7.43; 7.97]	6.95 (1.64) [6.23; 7.67]	$U = 505$; $p = .050$ $d = 0.59$
WISC-R IQ	123.52 (12.51) [120.59; 126.45]	117.25 (14.09) [111.07; 123.43]	$U = 519$; $p = .093$ $d = 0.49$
Word reading TP1, TP2 & TP3 (items read / minute)	19.60 (18.70) [15.22; 23.98] 50.39 (22.72) [45.07; 55.71] 74.17 (23.69) [68.62; 79.72]	3.80 (5.22) [1.51; 6.09] 20.60 (9.77) [16.32; 24.88] 35.30 (8.67) [31.50; 39.10]	$F(1,87) = 40.86$ $p < .001$*** $\eta_p^2 = .320$
Pseudoword reading TP1, TP2 & TP3 (items read / minute)	15.80 (13.41) [12.66; 18.94] 33.34 (10.20) [30.95; 35.73] 42.00 (11.21) [39.37; 44.63]	3.40 (4.98) [1.22; 5.58] 17.25 (7.96) [13.76; 20.74] 26.70 (6.66) [23.78; 29.62]	$F(1,86) = 40.77$ $p < .001$*** $\eta_p^2 = .322$
Phoneme analysis TP1, TP2 & TP3 (items solved)	7.79 (4.00) [6.85; 8.73] 10.26 (2.58) [9.66; 10.86] 10.61 (2.63) [9.99; 11.23]	3.05 (3.17) [1.66; 4.44] 8.65 (3.80) [6.98; 10.32] 10.30 (2.49) [9.21; 11.39]	$F(1,87) = 12.49$ $p < .001$*** $\eta_p^2 = .126$
Phoneme deletion TP1, TP2 & TP3 (items solved)	4.84 (4.36) [3.82; 5.86] 10.09 (3.44) [9.28; 10.90] 13.55 (4.60) [12.47; 14.63]	1.30 (2.36) [0.27; 2.33] 5.10 (4.47) [3.14; 7.06] 8.50 (4.81) [6.39; 10.61]	$F(1,87) = 25.46$ $p < .001$*** $\eta_p^2 = .226$

Note: *** - $p < .001$, ** - $p < .01$, * - $p < .05$ Mean (SD) [95% CI].

Experimental Design: fMRI Tasks

We applied the same fMRI tasks (Dębska et al., 2016) at both the first and the third time points. During the fMRI tasks, children heard twenty pairs of nouns (via headphones). The nouns were illustrated on pictures presented on the screen, visible for participants through an angled mirror. The exact list of the words used in the tasks is presented in Appendix 4. In the phonological task (Rhyme task) participants decided whether the nouns rhymed or not, similarly as in previous studies (Kovelman et al., 2012). In the control, non-phonological, task children assessed whether the nouns were spoken by speakers of the same gender (Voice task; Raschle et al., 2012). The Rhyme task and the Voice task included exactly the same stimuli (Appendix 4). The participants responded by pressing the corresponding buttons. The Rhyme and the Voice tasks were further compared to a rest condition, during which participants looked at a fixation cross for the duration of one block. The accuracy and reaction times at both time points were analyzed with the use of a repeated-measures ANOVA.

The testing procedure was the same for both time points which included fMRI tasks. Participants were familiarized with the tasks in a mock-scanner, on the basis of items which were not included in the further testing. The procedure included two functional runs: one with the phonological Rhyme task, and one with the control non-phonological Voice task. The timing and duration of the two tasks were the same. The order of the two tasks was counterbalanced across the participants and reversed at the third as compared to the first time point. While children heard the words, the pictures appeared on the screen for 2 seconds. After presentation of the two words, a question mark was presented for 2 seconds, and prompted children to respond. Each run included ten blocks: five blocks with stimulation (four trials per block), and five with the rest condition. Half of the trials matched in rhyme and half of the trials matched in terms of speakers' gender (see Appendix 3). We used Presentation software (Neurobehavioral Systems) to present the stimuli.

fMRI Data Acquisition and Analyses

Neuroimaging data were acquired on a 3T Siemens Trio scanner using whole-brain echo planar imaging sequence with 12-channel head coil (34 slices, slice-thickness 3.5 mm, TR = 2 sec, TE = 30 msec, flip angle= 90°, FOV= 214 mm^2, matrix size: 64 × 64, voxel size 3.5 x 3.5 x 3.5 mm). Anatomical data were acquired using a T1-weighted sequence (176 slices, slice-thickness 1 mm, TR = 2.53 sec, TE = 3.32 msec, flip angle= 7°, matrix size: 256 × 256, voxel size 1 x 1 x 1 mm).

The data pre-processing and analyses were performed using Statistical Parametric Mapping (SPM12, Wellcome Trust Center for Neuroimaging, London, UK) running on MATLAB R2013b (The Math-Works Inc. Natick, MA, USA). All images were initially realigned to the participant mean. Next pairwise longitudinal registration was performed on T1-weighted images from two TPs and midpoint average image was created. This image was then segmented using pediatric tissue probability maps (Template-O-Matic toolbox was used with the matched pairs option). The functional images were normalized to MNI space via flow fields acquired from average T1-weighted image co-registered to mean functional image. Finally, the normalized images were smoothed with an 8 mm isotropic Gaussian kernel. The data was modelled for each run and each time point, using the canonical hemodynamic response function convolved with the experimental conditions. Besides adding movement regressors to the design matrix, ART toolbox was used to reject motion-affected volumes by modelling them in the design matrix. Artifactual volumes were identified using a movement threshold of 3 mm and a rotation threshold of 0.05 radians. Subjects were included if a minimum 80% of volumes from each run at each time point were artefact-free. There were no differences between children with and familial history of dyslexia in the number of rejected volumes at each time point.

The general linear approach implemented in SPM12 was used to conduct whole-brain statistical tests. For each subject individually, we contrasted experimental phonological and control non-phonological tasks (Rhyme > Voice) at each time point. In order to illustrate structures involved in phonological processing at each time point, we conducted a series of one-sample t-tests separately for children with dyslexia and typical readers. Next, to assess the developmental changes, we used paired t-tests separately for typical readers and for children with dyslexia. In order to examine the differences between groups at each time point, we performed two-sample t-tests. To test for group and time interaction, we applied a flexible factorial design implemented in SPM12, as an equivalent of two-way mixed-design factorial ANOVA. Results are reported at a significance level of $p < .005$ uncorrected, and extent threshold of 50 voxels, as in previous pediatric neuroimaging studies (Dębska et al., 2016; Langer et al., 2015; Raschle et al., 2012; Saygin et al., 2016; Wang et al., 2018). The anatomical structures were identified with the use of xjView toolbox.

Results

Behavioral Results

Children with dyslexia presented lower scores than typical readers in all reading and reading-related tests (see Table 8 and Figure 11). Difference between typical readers and children who developed dyslexia later on were already visible at the first time point. These differences regarded letter knowledge (the first two time points), word and pseudoword reading (at each time point), phoneme analysis (only at the first time because of ceiling effect at later time points) and phoneme deletion (at each time point). As estimated with partial eta squared (Table 8), the differences between the groups were either large (in case of reading measures and phoneme deletion, $\eta_p^2 > .14$) or of medium size (in case of phoneme analysis).

In-Scanner Performance

Children with dyslexia presented lower accuracy in the Rhyme task performed during the fMRI scanning, but only at the first time point (see Table 9), and the between-group difference was large as revealed with Cohen's d effect size. However, there were no differences between the groups either in accuracy in the Voice task at any time point, or in reaction times in the two in-scanner tasks.

Table 9. The performance in the fMRI tasks in typical readers and children with dyslexia in Experiment 2.

	Typical readers (*n* = 70)	**Dyslexic readers (*n* = 20)**	
Voice task: accuracy TP1 (percent of correct responses)	71.74 (20.24) [67.00; 76.48]	66.39 (20.28) [57.50; 75.28]	$U = 514$; $p = .297$; $d = 0.27$
Rhyme task: accuracy TP1 (percent of correct responses)	92.25 (12.88) [89.23; 95.27]	77.75 (21.73) [68.23; 87.27]	$U = 313$; $p < .001$***; $d = 0.96$
Voice task: accuracy TP3 (percent of correct responses)	87.75 (13.57) [84.57; 90.93]	81.25 (15.72) [74.36; 88.14]	$U = 515$; $p = .080$; $d = 0.47$
Rhyme task: accuracy TP3 (percent of correct responses)	93.91 (11.14) [91.30; 96.52]	90.50 (10.50) [85.90; 95.10]	$U = 513$; $p = .066$; $d = 0.31$
Voice task: reaction times TP1 (seconds)	1.96 (0.60) [1.82; 2.10]	1.94 (0.55) [1.70; 2.18]	$U = 654$; $p = .723$; $d = 0.04$
Rhyme task: reaction times TP1 (seconds)	1.71 (0.45) [1.60; 1.82]	1.87 (0.39) [1.70; 2.04]	$U = 539$; $p = .138$; $d = 0.38$
Voice task: reaction times TP3 (seconds)	2.13 (0.53) [2.01; 2.25]	2.19 (0.50) [1.97; 2.41]	$U = 669$; $p = .836$; $d = 0.11$
Rhyme task: reaction times TP3 (seconds)	2.04 (0.50) [1.92; 2.16]	2.14 (0.51) [1.92; 2.36]	$U = 568$; $p = .640$; $d = 0.19$

Note: *** - $p < .001$, ** - $p < .01$, * - $p < .05$ Mean (SD) [95% CI].

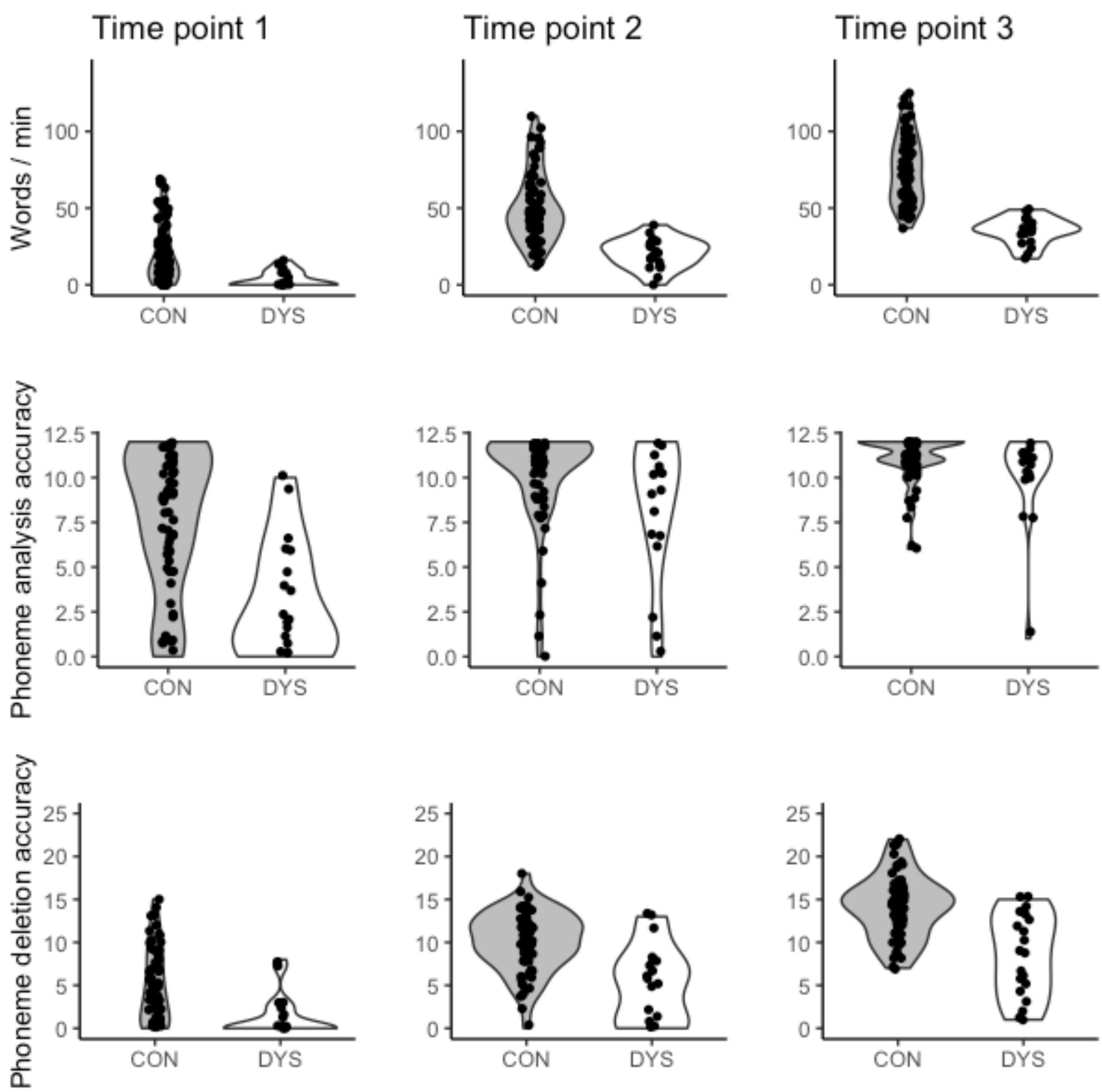

Figure 11 Word reading, phoneme analysis and phoneme deletion scores in typical readers (CON) and children with dyslexia (DYS) across three time points.

fMRI Results

Figure 12, Table 10 and Table 11 present brain activation to Rhyme > Voice contrast in typical and dyslexic readers at each time point. At the first time point, typical readers activated widespread brain areas including the bilateral inferior frontal areas, the middle, superior, inferior, and anterior temporal areas, the left fusiform gyrus and calcarine sulcus, the putamen and the cingulate cortex and caudate (subcortically). At the third time point, the areas engaged by typical readers were restricted to the bilateral putamen, caudate, and occipital areas.

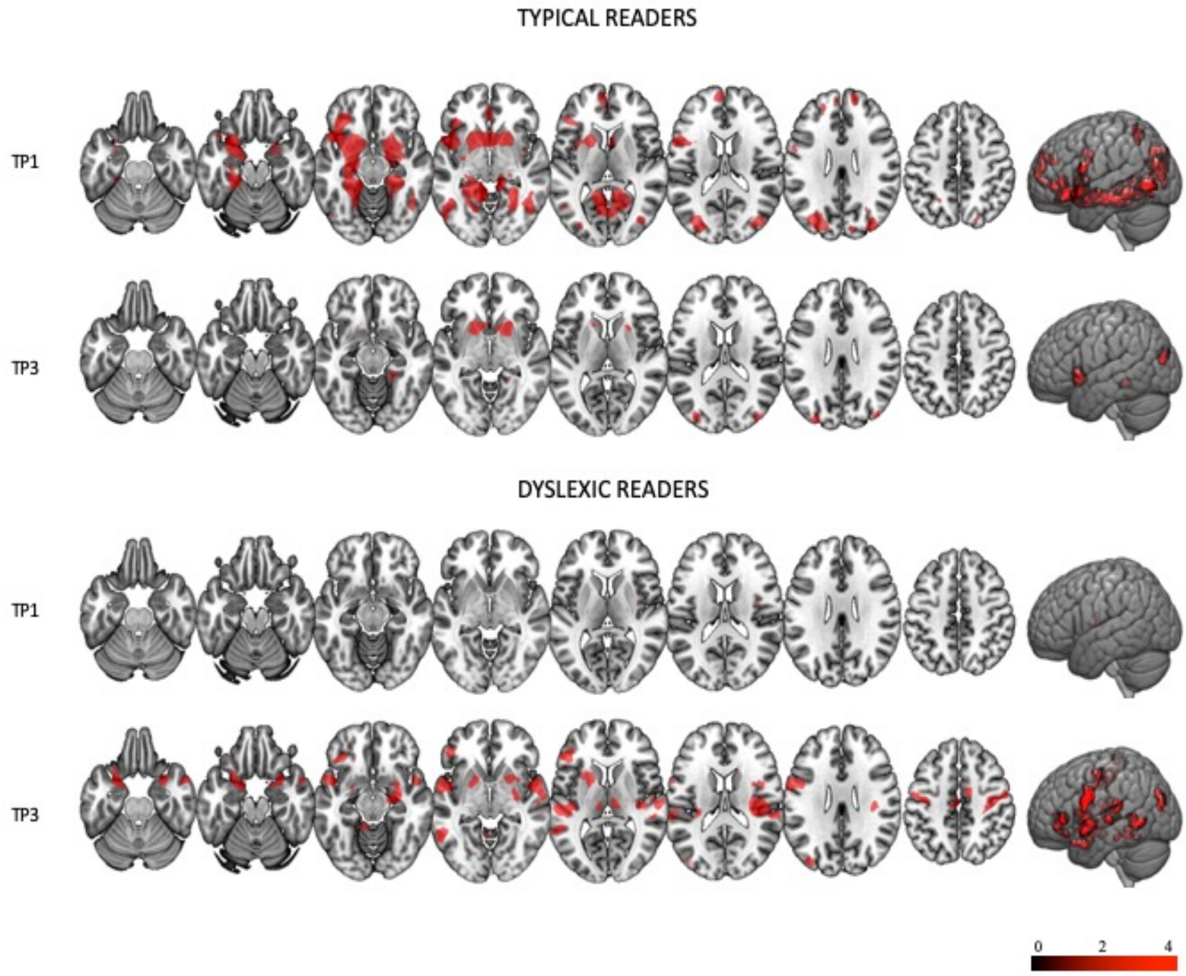

Figure 12. Rhyme > Voice contrast in typical readers and children with dyslexia at the first (TP1) and the third (TP3) time points as revealed by one-sample t-tests.

At the first time point, children with dyslexia showed modest activation in the right insula and precentral and postcentral gyri (Table 11 and Figure 12). At the third time point, dyslexic readers engaged numerous regions including the bilateral middle, superior temporal, and parietal areas, the bilateral inferior frontal areas, the left insula, the cerebellum, and subcortical structures such as the putamen, caudate, amygdala, and hippocampus.

Table 10. Significant activation in typical readers in Experiment 2 (Rhyme > Voice).

Brain region	H	x	y	z	Voxels	*t*	*p*
TP1							
Lingual (L, R), Putamen (L), Inferior Frontal (orb&tri, L), Hippocampus (L, R), Fusiform (L), Calcarine (L,R), Putamen (R), Caudate (R), Amygdala (L, R), Inferior temporal (R),Middle Temporal Gyrus (R)	L, R	-26	2	-16	9810	5.35	<.001
Middle & Superior Occipital, Cuneus	L	-32	-82	22	1062	3.93	<.001
Medial & Superior Frontal (L), Anterior Cingulate (L,R)	L, R	-6	58	20	529	3.72	<.001
Superior Frontal	R	14	56	26	126	3.66	<.001
Middle Temporal & Occipital, Inferior Temporal & Occipital	L	-52	-66	2	394	3.65	<.001
Precentral	L	-54	-4	48	57	3.55	<.001
Middle Temporal & Occipital, Superior Temporal	R	44	-80	14	596	3.46	<.001
Superior & Inferior Parietal	L	-24	-58	54	186	3.44	<.001
Middle Cingulum	L, R	0	4	36	118	3.42	.001
Calcarine	L	-8	-86	2	66	3.39	.001
Superior Occipital	R	22	-74	40	85	3.20	.001
Caudate	L	-14	26	4	115	3.19	.001
Superior Parietal	R	28	-56	66	65	3.09	.001
Cuneus	R	12	-88	26	54	2.98	.002
Medial & Superior Frontal	L	-22	52	32	82	2.90	.002
TP3							
Middle & Superior Occipital	R	42	-84	22	263	4.85	<.001
Putamen, Caudate	L	-16	12	-4	524	4.09	<.001
Putamen, Caudate	R	16	12	-4	548	3.99	<.001
Middle & Superior Occipital	L	-34	-90	24	295	3.66	<.001
Parahippocampal, Fusiform	R	24	-38	-10	166	3.58	<.001

Table 11. Significant activation in children with dyslexia in Experiment 2 (Rhyme > Voice).

Brain region	H	x	y	z	Voxels	*t*	*p*
TP1							
Insula, Precentral & Postcentral Gyri	R	38	-10	12	139	3.32	.002
TP3							
Superior Temporal, Precentral, Rolandic Operculum, Heschl, Postcentral, Temporal Pole, Middle Temporal, Supp Moto Area, Putamen	R	30	-30	20	3597	5.36	<.001
Middle & Inferior Temporal	L	-58	-52	-4	367	5.29	<.001
Superior & Middle Temporal, Heschl	L	-52	-26	6	577	5.20	<.001
Superior Temporal, Rolandic Oper	L	-50	6	-12	445	4.96	<.001
Insula	L	-28	-30	20	90	4.82	<.001
Middle Occipital	L	-40	-86	22	189	4.80	<.001
Inferior Frontal (orb, tri)	L	-48	32	4	394	4.78	<.001
Precentral & Postcentral, Inferior Frontal (oper)		-60	2	26	765	4.72	<.001
Putamen, Inferior Frontal (orb), Temporal Pole (sup), Caudate, Amygdala	L	-26	6	-24	1412	4.57	<.001
Putamen, Amygdala, Hippocampus, Temporal Pole (sup)	R	10	-30	-10	803	4.55	<.001
Precentral & Postcentral, Inferior Frontal (oper)	R	30	-30	74	171	4.28	<.001
Thalamus	R	12	-20	6	127	4.19	<.001
Cerebellum (IV, V), ParaHippocampal, Fusiform	L	-6	-48	-8	208	4.15	<.001
Thalamus	L	-10	-20	2	85	4.06	<.001
Middle Cingulate	L	-2	-16	46	77	3.18	.002

The found differences between typical readers and children with dyslexia were as follows. At the first time point, children who later developed dyslexia during had reduced activation in the left middle and inferior occipital gyri, as compared to future typical readers (Figure 13, Table 12). There were no regions engaged by poor readers but not by typical readers at the first time point. On the other hand, at the third time point, children with dyslexia presented higher activation than typical readers in several brain areas. The higher activation of children with dyslexia as compared to typical readers were found in the bilateral superior temporal gyrus (STG), middle temporal gyrus (MTG), Heschl's gyri (HG), Rolandic operculum and insula, but also in the left supramarginal gyrus (SMG), precentral and postcentral gyri, and subcortically in the right putamen. At the third time point, there were no brain areas activated by typical but not by dyslexic readers.

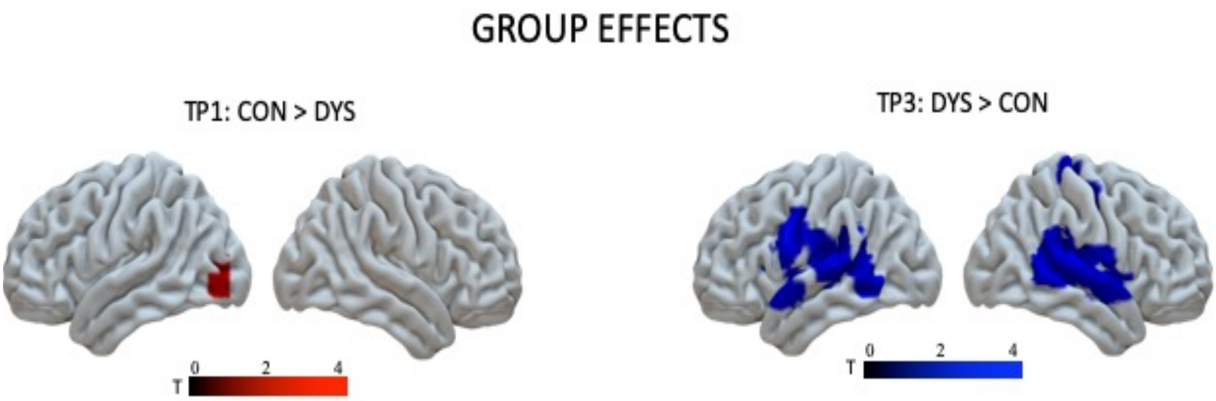

Figure 13. Effects of dyslexia (typical readers, CON, versus children with dyslexia, DYS) at the first (TP1) and the third (TP3) time points as revealed by two-sample t-tests.

At later reading acquisition stage as compared to the beginnings of education, typically reading children showed a reduction of brain activation in the language regions of the left hemisphere (STG, insula, inferior frontal gyrus: IFG, precentral gyrus: PrCG, superior and inferior parietal lobules: SPL, IPL, hippocampus; Table 12 and Figure 14). There were no regions more activated by typical readers at the third than at the first time point. In children with dyslexia, brain activation during phonological processing in the right STG and insula increased with time (Table 12, Figure 14), and there were no areas activated in the first but not in the third time point. Diverging developmental trajectories related to literacy acquisition in typical readers and children with dyslexia were confirmed in a time x group interaction present in the bilateral STG, insula, left MTG, and right frontal cortex (Table 12, Figure 15). In these regions typical readers presented an decrease of activation with time, while dyslexic readers showed an increase of activation.

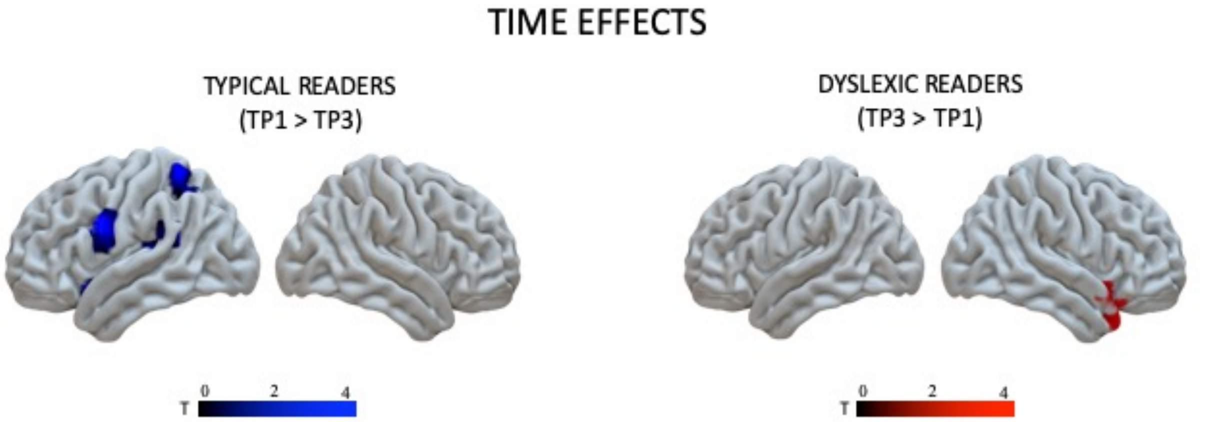

Figure 14. Effects of time (the first versus the third time point) in typical readers and in children with dyslexia as revealed by paired t-tests.

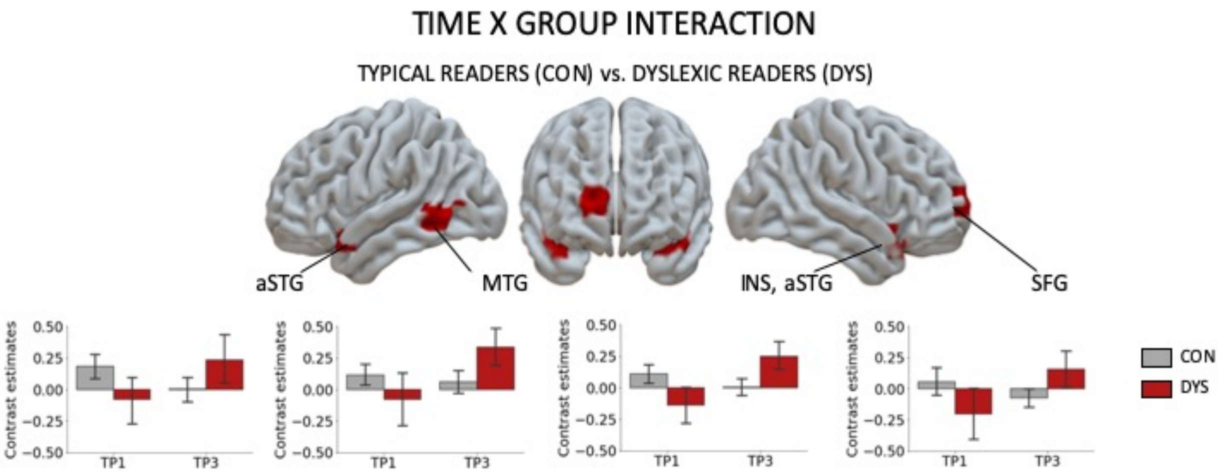

Figure 15. The interaction of effects of group (typical readers versus children with dyslexia) and time (TP1 versus TP3) as revealed in flexible factorial design.

Table 12. Significant group and time point effects in typical readers and children with dyslexia in Experiment 2.

	Brain region	H	x	y	z	Voxels	*t*	*p*
Group Effects	**TP1 CON > DYS**							
	Middle & Inferior Occipital Gyri	L	-38	-82	-4	71	3.11	.001
	TP3 DYS > CON							
	Middle & Superior Temporal Gyri, Rolandic Operculum, Heshl Gyrus, Insula, Postcentral Gyrus	R	32	-32	24	2401	4.96	<.001
	Cingulate Gyrus	L	-12	-2	30	359	4.21	<.001
	Superior Temporal Gyrus, Postcentral Gyrus, Heschl Gyrus	L	-60	-30	14	785	4.10	<.001
	Inferior Parietal Lobule, SupraMarginal Gyrus	L	-46	-42	26	169	4.05	<.001
	Postcentral & Precentral Gyri, Inferior Frontal Gyrus (oper)	L	-54	0	28	484	4.05	<.001
	Superior Temporal Gyrus, Insula	R	52	-2	-4	224	3.57	<.001
	Hippocampus, Putamen	R	30	-12	-12	127	3.56	<.001
	Middle Temporal Gyrus	L	-52	-48	6	148	3.46	<.001
	Superior Temporal Gyrus	L	-60	6	-12	100	3.37	.001
	Precentral Gyrus	R	24	-30	68	53	3.06	.001
	Insula, Superior Temporal Gyrus	L	-36	-8	-2	98	3.06	.001
	Precentral Gyrus	R	38	-14	52	60	2.95	.002
TP Effects	**CON TP1 > TP3**							
	Precentral Gyrus	L	-54	0	28	102	3.54	<.001
	Inferior Frontal Gyrus (orb), Insula, Superior Temporal Gyrus	L	-30	6	-18	104	3.45	<.001
	Superior Parietal Lobule	L	-24	-54	44	59	3.44	<.001
	Inferior Parietal Lobule	L	-38	-52	62	56	3.43	.001
	Inferior Frontal Gyrus (oper)	L	-34	12	18	60	3.33	.001
	Hippocampus	L	-24	-28	0	140	3.31	.001
	Lingual, Cerebellum (IV, V)	L	-10	-52	0	74	3.27	.001
	SupraMarginal Gyrus, Superior Temporal Gyrus	L	-44	-42	24	64	3.21	.001
	DYS TP3 > TP1							
	Superior Temporal Gyrus, Insula	R	38	22	-26	114	4.11	<.001
Interaction	**CON TP1>TP3 & DYS TP3>TP1**							
	Superior & Medial Frontal Gyri	R	16	62	8	88	3.46	<.001
	Middle & Inferior Temporal Gyri	L	-58	-62	0	135	3.34	.001
	Insula, Superior Temporal Gyrus	R	42	12	-14	61	3.25	.001
	Superior Temporal Gyrus	L	-30	6	-22	61	2.91	.002

Note: Group effects were tested with one-way ANOVA, TP effects were tested with paired t-tests, Group and TP interaction was tested with flexible factorial design. CON – typical readers, DYS – children with dyslexia

Discussion

In the present Chapter, we explored longitudinally how neural correlates of phonological processing change during the two first years of education in typical readers and in children with dyslexia. We first analysed the phonological and reading development of the two groups and then assessed the brain activation during phonological processing.

Children with dyslexia presented lower scores than typical readers in reading and phonological awareness tasks at each time point, even at the very beginning of education. Similar early differences between typical and impaired readers have been also reported in other transparent orthographies, such as Czech and Slovak (Moll et al., 2016), Dutch (Dandache et al., 2014), Finnish (Torppa et al., 2010) and German (Schneider et al., 2000). These early differences were even higher in opaque languages such as English (Gallagher et al., 2000). This suggest that across various orthographies, behavioural differences between future typical and dyslexic readers may be observed much earlier than after several years of education.

On the neural level, at the beginning of education, when children attended the first grade or still were in kindergarten, we found reduced activation of the left visual cortex in children with future dyslexia. This hypoactivation is consistent with previous fMRI studies on visual and orthographic processing in dyslexia (Boros et al., 2016; Cao et al., 2018; Dehaene et al., 2010).

However, two years later children with dyslexia presented increased activation as compared to typical readers. This higher activation was present in the bilateral temporal cortices including the auditory cortex, as well as in the left supramarginal and precentral and postcentral gyri, and in the putamen (subcortically). These areas are typically associated with the neural phonological network (Brennan et al., 2013) and were also engaged by typical readers at the beginning of education . The observed overactivation in the dyslexic group may suggest that children with dyslexia present a delay in the development of phonological brain network (Morken et al., 2017; Raschle et al., 2011), as after 2 years of education they engage the areas that typical readers activated at an earlier stage of reading development. However, the issue whether dyslexia is a developmental delay or a deficit with an altered developmental pathway is still being discussed. With respect to phonological skills in dyslexic readers, a cross-sectional study applied a developmental trajectory method (Thomas et al., 2009) and revealed a delayed trajectory for phonological short term memory and an atypical trajectory for phonological awareness (Kuppen & Goswami, 05 2016). An atypical rather than delayed phonological brain network in dyslexia was also found in a cross-sectional fMRI study in which children with dyslexia showed reduced activation during a rhyme judgment task in the bilateral temporo-parietal and frontal cortex as compared to both reading-matched and age-matched children (Hoeft et al., 2006). However, cross-sectional studies cannot definitively distinguish between atypical and delayed development of the phonological brain network. More longitudinal studies are needed to resolve this debate. As the data presented in the current Chapter covers only the first two years of education, we are not allowed to predict what happens with the phonological network after this period. Nor can we say whether or not the activations observed in the dyslexic group would begin to resemble those of typical readers or whether their behavior over time will be the same.

At the very first stage of literacy acquisition, typical readers engaged not only structures typically involved in phonological processing (bilateral superior and middle temporal gyri, left IFG) but also those involved in semantic analysis of words (anterior temporal areas) and in movement planning (premotor and motor areas, caudate, putamen). The expected and found decrease of activation over time in the phonological network, especially in the left perisylvian areas, suggests that with growing reading experience (or with passing time), typical readers automatize phonological processing and therefore the neural circuitry becomes more specialized (Dębska et al., 2016; Pugh et al., 2013; Yu et al., 2018). This result contrasts with the age-related increases in brain activation reported in cross-sectional studies (Brennan et al., 2013; Cone et al., 2008). The reductions of activation observed in the current study are more spread (not restricted to left IPL) than what was found in the only previous longitudinal study of typical readers (Yu et al., 2018). This difference may result from a bigger sample size and a longer time period between the two time points in the current study.

After two years of reading acquisition, children with dyslexia showed an increase of brain activation. They also activated the right hemisphere superior temporal cortex. The right hemisphere is usually employed for reading by children who have just learned to read (Waldie & Mosley, 2000) and its activity reduces as children master reading (Shaywitz et al., 2007). Previous studies mentioned also compensatory shifts to right hemisphere in dyslexia in terms of activation increases (Shaywitz et al., 2007; Simos et al., 2007). The interaction of time and group, i.e. the increase of activation in the dyslexic group and simultaneous decrease of activation in typical readers, observed in the bilateral STG, insula, left MTG, and right frontal cortex supports the hypothesis of a delay in the development of phonological structures in dyslexic readers (Morken et al., 2017; Raschle et al., 2011). As these brain regions were engaged by typical readers only at the beginning of education, and by dyslexic children who were two years older, they seem to be employed non-proficient phonological processing related to low reading skills.

To summarize, in the Experiment 2 we found that children who typically develop reading, present activation of phonological regions such as bilateral superior and middle temporal gyri, left IFG already at the beginning of formal literacy education. Over time, the typical readers reduce the activation of the phonological network (especially of the perisylvian areas). On the other hand, children with dyslexia show a delay in development of the phonological neural network, as after two years of learning to read they employed the areas engaged by typical readers only at the very beginning of education.

Chapter 8. Intervention based on phonological and attentional video games: Experiment 3

In the two previous Chapters we searched for a phonological and a visual attention span deficits in Polish children with dyslexia, and for the neural basis of the phonological deficit. In the current Chapter we continue the topic of the phonological and visual attention basis of dyslexia by comparing the efficiency of two interventions, addressing these two skills. As described in Chapter 4, both phonological trainings and trainings which used action video games (AVG) could lead to improvements of reading skills, as an effect of increase of either visual attention or phonological awareness. In the current Chapter we try to replicate the previous enthusiastic reports on the efficiency of particular AVG used to improve reading of English and Italian children with dyslexia (Franceschini et al., 2013, 2017). The second intervention method was based on phonological non-action video games (PNAVG) and differed from the non-action games employed by previous studies. While previous research selected NAVG that had no impact on reading, we chose a NAVG which could potentially improve reading, as trainings of phonological awareness lead to increase of reading skills (Bus & van IJzendoorn, 1999; Ehri et al., 2001). The PNAVG used in the study were based on pure phonological processing, without any action or reading-related aspects, what enabled us to access the efficiency of a purely phonological computer-based intervention.

What is crucial for the study described in the current Chapter, in addition to the two training groups, we included a control group who did not take part in any video-game-based intervention. This control group consisted of children with dyslexia who completed the same series of web-based assessment of reading skills as the experimental groups. The inclusion of a non-training control group made it possible not only to compare the two interventions but also to assess their efficiency as compared to regular development or simple task learning effects.

Finally, in the current Chapter we explored whether the effectiveness of the two interventions depends on the presence of given deficits in the participants. In particular, we compared the progress in reading and in cognitive skills between children with and without a phonological deficit. The partial results and the design of the study were described in a separate publication (Łuniewska et al., 2018).

Research questions

In the current Chapter we aimed at assessing the effectiveness of the two interventions: based on AVG and on PNAVG. We expected that the effectiveness of the trainings would be reflected in the progress in the reading-related tasks. In particular, we supposed that the improvement of the reading scores in the two training groups would be higher than in the non-training control group, as both AVG and phonological interventions have been shown to increase reading scores in children with dyslexia.

We also expected that the trainings would lead to increase of the skills related to the type of the games. Namely, we anticipated a higher progress in phonological skills (as measured with phoneme deletion and vowel replacement tasks) in the group playing PNAVG, and a more pronounced improvement of visual (selective) attention in the players of AVG.

Additionally, we tested whether the effectiveness of the two trainings differs between children with and without a phonological deficit. In particular, we expected that the PNAVG training would be more effective in improving reading and phonological skills of children with a phonological deficit (measured one year earlier) than in children without a phonological deficit. On the other hand, we assumed that the effectiveness of the AVG training would not interact with the level of phonological skills.

Method

Participants

The participants were recruited from the broader study on dyslexia (see Experiment 1a). All participants of the training and all members of the dyslexic control group had a diagnosis of dyslexia confirmed in the Experiment 1a. The participants were invited for the training about one year after the testing sessions, and therefore they are about one year older than in the Experiment 1a.

Training groups

The participants of the training were fifty-four children with dyslexia. To the experimental groups we selected those participants whose families were able to arrive to the Nencki Institute where the training took place, 18 times in six weeks. In practice, this condition implied that all participants of the trainings were living in or around Warsaw.

The participants were randomly assigned to one of two groups, either playing attentional video games (AVG; n = 27), or playing phonological non-attentional video games (PNAVG; n = 27). A detailed comparison of the two training groups is presented in the Table 13. The groups did not differ in terms of any demographic variable (age, gender, school grade). Also, the reading skills as well as reading-related skills such as phonological awareness and rapid automatized naming did not differ between the two training groups.

Among the participants there were 26 children (equally distributed between the AVG and PNAVG groups) who had a phonological deficit as defined and measured in the Experiment 1a (i.e. the phonological factorial score below the threshold of the 10th percentile in the control group), and 28 children who did not show a deficit of phonological awareness. The group included also seven children who had a visual attention span deficit (four AVG and three

PNAVG players) but as the visual attention span deficit was shown to be unstable over time and the group was very small, we did not include this variable in the analyses.

Table 13. Attentional video games and phonological non-attentional video games players in Experiment 3.

	AVG (***n*** **= 27**)	**PNAVG** (***n*** **= 27**)	
Gender	Female: 9 Male: 18	Female: 9 Male: 18	$Chi^2(1)= 0.00$, $p = 1.00$
School grade	3rd grade: 2, 4th grade: 15 5th grade: 5, 6th grade: 5	3rd grade: 3, 4th grade: 9 5th grade: 10, 6th grade: 5	$Chi^2(3) = 3.37$, $p = .34$
Age (years)	11.04 (1.00) [10.66; 11.42]	10.96 (1.00) [10.58; 11.34]	$t(52) = 0.28$, $p = .79$, $d = 0.08$
Word list reading (items read correctly in a minute)	49.15 (13.85) [43.93; 54.37]	48.59 (18.05) [41.78; 55.4]	$t(52) = 0.13$, $p = .90$, $d = 0.03$
Pseudoword list reading (items read correctly in a minute)	32.67 (6.63) [30.17; 35.17]	30.67 (7.38) [27.89; 33.45]	$t(52) = 1.05$, $p = .30$, $d = 0.29$
Phoneme deletion (correct responses, max = 16)	10.93 (2.77) [9.89; 11.97]	10.96 (2.90) [9.87; 12.05]	$t(52) = -0.05$, $p = .96$, $d = 0.01$
Phoneme deletion (time to solve 16 items, in seconds)	133.63 (30.31) [122.2; 145.06]	142.23 (46.85) [124.56; 159.9]	$t(52) = -0.80$, $p = .43$, $d = 0.22$
Vowel replacement (correct responses, max = 24)	18.59 (5.83) [16.39; 20.79]	19.8 (3.24) [18.58; 21.02]	$t(52) = -0.91$, $p = .37$, d= 0.26
Vowel replacement (time to solve 16 items, in seconds)	91.48 (26.07) [81.65; 101.31]	98.32 (33.52) [85.68; 110.96]	$t(52) = -0.83$, $p = .41$, $d = 0.23$
Pseudoword repetition (correct responses, max = 27)	24.15 (1.66) [23.52; 24.78]	23.96 (2.50) [23.02; 24.9]	$t(52) = 0.32$, $p = .75$, $d = 0.09$
Rapid automatized naming: object (time in seconds)	46.48 (9.18) [43.02; 49.94]	46.48 (11.42) [42.17; 50.79]	$t(52) = 0.00$, $p = 1.00$, $d = 0.00$
Rapid automatized naming: colours (time in seconds)	50.37 (8.78) [47.06; 53.68]	52.48 (17.10) [46.03; 58.93]	$t(52) = -0.57$, $p = .57$, $d = 0.16$
Rapid automatized naming: digits (time in seconds)	26.67 (5.23) [24.7; 28.64]	29.19 (9.21) [25.72; 32.66]	$t(52) = -1.24$, $p = .22$, $d = 0.34$
Rapid automatized naming: letters (time in seconds)	28.70 (6.66) [26.19; 31.21]	31.81 (10.27) [27.94; 35.68]	$t(52) = -1.32$, $p = .19$, $d = 0.36$
Selective attention (number of correct responses)	63.00 (9.33) [59.48; 66.52]	63.30 (13.53) [58.20; 68.40]	$t(52) = -0.09$, $p = .93$, $d = 0.03$

Note: Mean (SD) [95% CI].

Control group

Additionally to the two experimental groups, we included a dyslexic control group (n = 16). The only substantial difference between the participants of the trainings and the dyslexic control group was that the representatives of the dyslexic control group could not arrive to the Nencki Institute 18 times in six weeks, as the majority of them did not live in Warsaw area. The control group did not differ from the training groups in terms of age, intelligence, reading skills, phonological awareness nor rapid automatized naming (see Table 14).

Table 14. The dyslexic control group the participants of trainings in Experiment 3.

	CONDYS (n = 16)	**AVG (n = 27)**	**PNAVG (n = 27)**	
Age (years)	11.51 (1.55) [10.75; 12.27]	11.04 (1.00) [10.66; 11.42]	10.96 (1.00) [10.58; 11.34]	$F(2,67) = 1.27, p = .29$ $\eta_p^2 = 0.037$
WISCR IQ	114.94 (9.84) [110.12; 119.76]	114.19 (13.10) [109.25; 119.13]	112.19 (11.03) [108.03; 116.35]	$F(2,67) = 0.34, p = .71$ $\eta_p^2 = 0.010$
Word reading (accuracy) [a]	2.94 (1.39) [2.26; 3.62]	2.85 (1.23) [2.39; 3.31]	2.78 (1.22) [2.32; 3.24]	$F(2,67) = 0.08, p = .92$ $\eta_p^2 = 0.002$
Pseudoword reading (speed) [a]	2.56 (0.73) [2.20; 2.92]	2.74 (1.16) [2.30; 3.18]	2.56 (1.12) [2.14; 2.98]	$F(2,67) = 0.25, p = .78$ $\eta_p^2 = 0.007$
Phonological awareness (accuracy) [a]	3.13 (1.92) [2.19; 4.07]	3.52 (1.40) [2.99; 4.05]	3.07 (1.77) [2.40; 3.74]	$F(2,66) = 0.53, p = .59$ $\eta_p^2 = 0.016$
Phoneme deletion (accuracy) [a]	3.94 (1.65) [3.13; 4.75]	3.48 (1.72) [2.83; 4.13]	3.44 (1.76) [2.78; 4.10]	$F(2,67) = 0.47, p = .63$ $\eta_p^2 = 0.014$
RAN: objects and colors (speed) [a]	3.13 (2.00) [2.15; 4.11]	3.04 (1.95) [2.30; 3.78]	2.96 (1.79) [2.28; 3.64]	$F(2,67) = 0.04, p = .96$ $\eta_p^2 = 0.001$
RAN: digits and letters (speed) [a]	3.81 (1.72) [2.97; 4.65]	3.52 (2.05) [2.75; 4.29]	2.70 (1.59) [2.10; 3.30]	$F(2,67) = 2.30, p = .11$ $\eta_p^2 = 0.064$

Note: [a] Standard ten scores (sten) are reported. Population mean equals 5.5 (2.0).
RAN – Rapid automatized naming. Mean (SD) [95% CI].

Procedure

Training procedure

Participants were not familiar with the games used for trainings. The training procedure included 18 sessions: two testing sessions at the beginning and at the end of the training, and 16 training sessions in-between. The first testing session was applied between 1 and 18 days (*M* = 9.2, *SD* = 4.4) prior to the training, and the second testing session was done between 1 and 18 days (*M* = 8.0, *SD* = 5.1) after the end of the training. The training included 16 sessions, each lasting 50 minutes (13.3 hours of training in total). The total time of training varied between 22 and 36 days (*M* = 28.9, *SD* = 2.1).

Children played the video games on 14-in laptops with the use of computer mouses and headphones. While playing the games, participants were seated in a room with two to eight other participants of the training or alone. Participants of AVG and PNAVG trainings were aware of the another game played by the other group, though never played the other game.

The attentional video game used in the experiment was the same as in the previous studies (Franceschini et al., 2013, 2017): *Rayman Raving Rabbids* from Ubisoft™. The game included several minigames, though only the minigames listed as action games (Franceschini et al., 2013) were applied. The training sessions were supervised by experimenters, who watched the screens of the players and monitored that the participants were playing only the selected minigames.

The phonological non-attentional video games were designed for the purpose of the experiment. The games were based on training of phonological awareness and did not include any components of action (Green et al., 2010). In the games, we used words and pseudowords presented orally with or without accompanying pictures. Children's task differed between the minigames, and was to (i) select words of a proper phonological characteristics, e.g. words ending with a specified phoneme, (ii) pair words according to a rule, e.g. words of the same length in phonemes, (iii) pair pseudowords according to a rule, e.g. words ending with the same phoneme, (iv) compose a pseudoword from heard phonemes or syllables, (v) blend syllables of two pseudowords, (vi) type a letter or a syllable which differentiated two words or pseudowords. Detailed description of the phonological games is provided as Appendix 4.

Direct testing procedure

The testing sessions before and after the training were performed in the same conditions. Participants' reading skills, phonological awareness and visual attention were tested individually during a one-hour-long session. The experimenters who administered the testing were not aware to which group the children belonged.

The reading and phonological tasks were used in two versions (A and B). The versions differed in terms of the exact items but not the procedure (Appendix 5). The order of the versions was counterbalanced across the time points and the participants, in such a way that half of the training participants were tested with the use of the version A in the pretest and the version B in the posttest, whereas the second half was initially tested with the version B, and the version A was applied in the posttest.

Reading was assessed by word and pseudoword reading tasks. Reading of words (two lists of 75 items) and pseudowords (two lists of 69 items) were assessed separately. Children read aloud as many words as they could in 30 seconds, then the procedure was repeated for the second list of the same type of items. Versions A and B differed in the order of the two lists among each category. We calculated the total number of correctly read items in a minute (sum of the two lists) and the number of read syllables for words and pseudowords separately.

A standardized pseudoword repetition task was applied (Szewczyk et al., 2015) to assess phonological memory. The task included 27 pseudowords of phonological properties similar to those of Polish words, and we calculated the number of correctly repeated pseudowords for each child.

We used a phoneme deletion task designed exclusively for the purposes of the current study. The task contained 16 items, and versions A and B differed in terms of exact items. Both accuracy and time necessary to finish the task (in seconds) were considered in the analyses.

A vowel replacement task was prepared for the purposes of the current study as a relatively difficult phonological task. We asked participants to repeat existing words with replacements of all occurrences of the 'a' vowel with either 'ɛ' (in the variant A) or 'u' (in the variant B). The task consisted of eight one-syllable words (e.g. 'park') and eight two-syllable words (e.g. 'brama'). Both accuracy of 24 replacements and time necessary to complete the task were calculated for the analyses.

Selective attention was measured with a subtest of IDS Intelligence Scale (Jaworowska et al., 2012). The task consisted of 225 pictures of ducks (9 lines of 25 pictures). Participants were asked to cross out all the ducks which fulfilled following criteria: were looking to the right (not to the left) and had exactly two body parts (such as legs or beak) marked with orange color. There were about ten target ducks in each line of 25 ducks. The time limit for each line was 15 seconds. We calculated the difference between the number of correctly and incorrectly crossed out ducks for each child.

Rapid automatized naming (RAN) was assessed with a standardized battery (Fecenec et al., 2013), in which children were asked to name the items presented on the boards as fast as possible. The battery of RAN tasks consisted of boards of objects, colors, digits and letters, presented in eight lines of six items. We measured the time of naming of the 48 items separately for each board.

Web-based reading tasks: word recognition, sentence reading and decoding

In order to compare the progress of reading in children who participated in the trainings and in the dyslexic control group, who did not take part in any intervention, we applied three web-based tasks. The tasks are described in details in the Appendix 6.

The three tasks included: word recognition task, in which participants selected existing words (one of three in each set, e.g. a word 'własny' exists in Polish, while 'właspy' and 'młasny' do not), sentence reading task, in which participants assessed whether simple read sentences are true or false, and decoding task, in which participants selected words pronouced differently from others in the set (e.g. 'fidzka' and 'ficka' sound the same in Polish, whereas 'fizka' is pronounced differently). The tasks had a rigorous time limit (different in the tasks), so that children could not complete all items. The tasks were repeated four times during each testing. We calculated the total number of correct responses given before the time limit in all four iterations of each task.

Children completed the web-based tasks remotely, working from home. The participants of the interventions completed the tasks approximately a month before the training (18–38 days to the intervention onset, *M* = 30.0, *SD* = 6.1), in the week preceding the training (0–7 days to the intervention onset, *M* = 1.5, *SD* = 1.5), closely after the training (0–18 days after the end of the training, *M* = 4.8, *SD* = 4.5) and, finally, around a month after the training (20–60 days after the training, *M* = 40.9, *SD* = 6.9). The control dyslexic group completed the web-based tasks on four testing sessions approximately one month apart (16–60 days, *M* = 38.3, *SD* = 10.8). As we aimed at comparing directly the effects of the intervention across the groups, we compared the data from the second and third testing, i.e. directly before and directly after the training.

Statistical analyses

We first applied a series of repeated-measures ANOVAs to compare the reading progress across the three groups (AVG versus PNAVG versus control dyslexic group) between the two measurements (second and third testing, as described above) in the three web-based reading tasks.

Similarly, we applied a series of repeated-measures ANOVAs with group (AVG versus PNAVG) as a between-subjects factor and time (before versus after intervention) as a within-group factor. This model was used for assessment of progress in phonological tasks, selective attention and rapid automatized naming. In case of reading, we additionally included the within-group factor of task (word versus pseudoword reading).

Finally, we used a series of repeated-measures ANOVAs with group (AVG versus PNAVG) and presence of phonological deficit (present versus lack of deficit) as between-subject factors and time (before versus after intervention) as a within-group factor with cognitive tasks (phonological tasks, selective attention, rapid automatized naming) and reading assessment (word and pseudoword reading assessed separately) as dependent variables.

The R script used for the data analyses and visualization is included in Appendix 7.

Results

Reading improvements as compared to the dyslexic control (no-training) group

We compared the progress in the three web-based reading tasks across the three groups (AVG, PNAVG and control dyslexic group). In the ANOVA model, we expected to find a significant interaction of time and group, which would suggest that the increase of reading scores was higher in the training than in the control group. As shown on the Figure 16, in case of the word recognition task, We found no significant effects of time ($F(1,66) = 3.12$, $p = .08$), group ($F(2,66) = 0.17$, $p = .84$) and time and group interaction ($F(2,66) = 1.41$, $p = .25$).

We found a significant increase of speed of sentence reading with time ($F(1,65) = 4.03$, $p = .049$, $\eta^2 = 0.06$), although we found no effect of group ($F(2,65) = 0.33$, $p = .72$) or interaction ($F(2,65) = 0.08$, $p = .92$). Similarly, we found an increase of decoding speed over time ($F(1,65) = 9.67$, $p = .003$, $\eta^2 = 0.13$) with no group difference ($F(2,65) = 0.43$, $p = .65$) or group and time interaction ($F(2,65) = 2.39$, $p = .10$). To summarize, we found an increase of scores with time in the two out of three tasks, but we found no difference between the intervention and the control group.

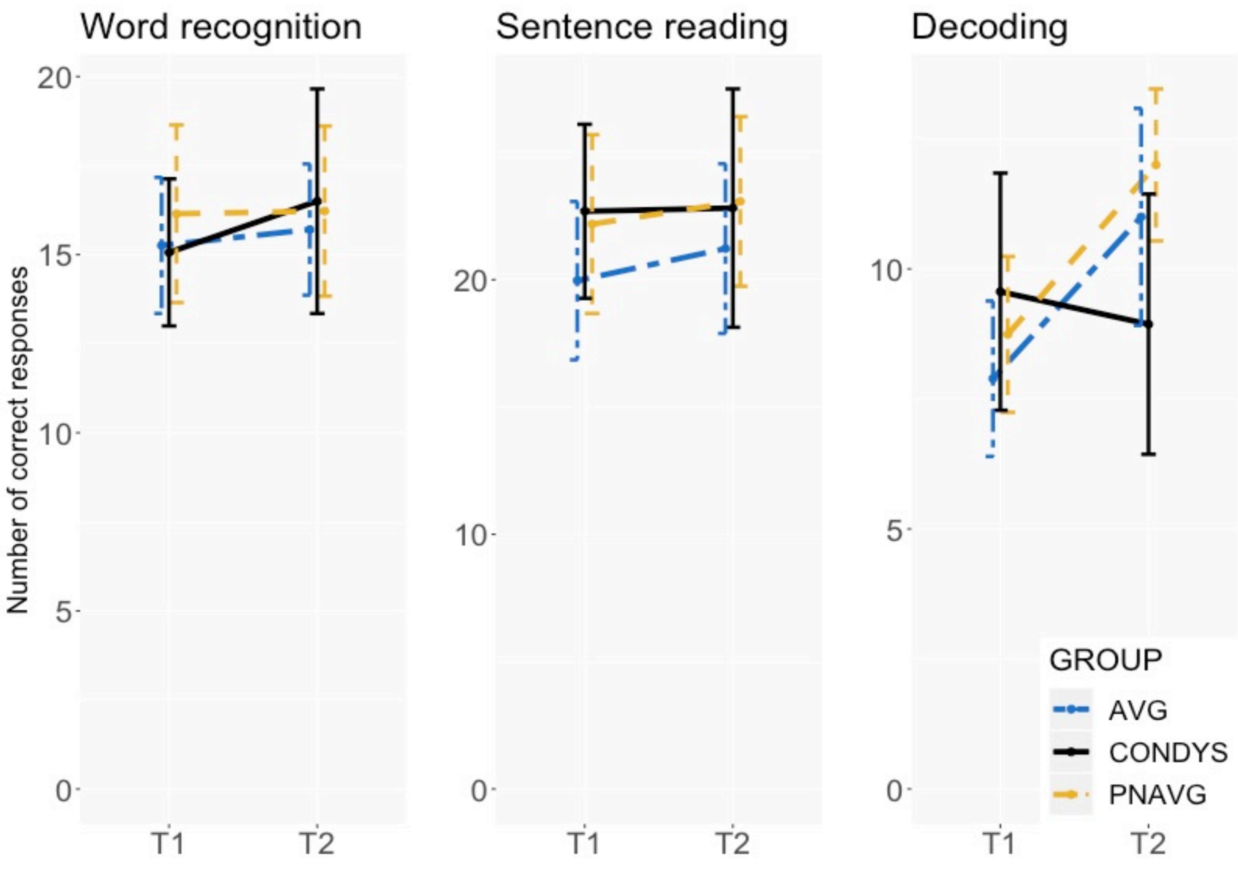

Figure 16. Increase of the reading scores between before the training (T1) and after the training (T2) in participants of the AVG (blue dot-dashed line), PNAVG (yellow dashed line) and dyslexic control group (black solid line). Error bars correspond to 95% confidence intervals. In sentence reading and decoding there was an effect of Time but there was neither effect of Group nor Group * Time interaction.

Reading improvement as compared between AVG and PNAVG players

While analyzing the number of items correctly read in a minute, we found a significant main effect of task ($F(1,52) = 110.34$, $p < .001$, $\eta^2 = 0.68$): participants were able to read more words than pseudowords (see Figure 17). We found also a significant main effect of time ($F(1,52) = 41.82$, $p < .001$, $\eta^2 = 0.45$), as children read more words after than before the training. Neither group ($F(1,52) = 0.29$, $p = .60$) nor interaction of group and time ($F(1,52) = 0.29$, $p = .59$) were significant.

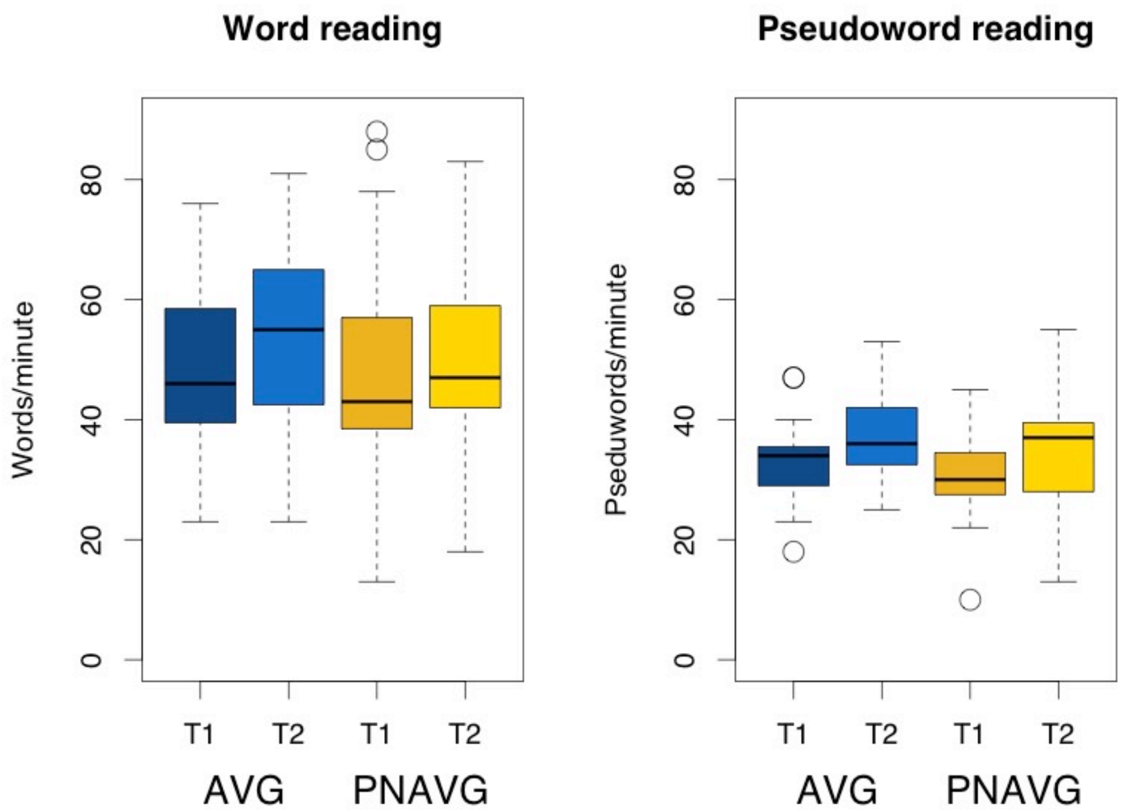

Figure 17. Reading scores (words and pseudowords correctly read per minute) across AVG (blue) and PNAVG (yellow) groups before (T1) and after (T2) the training.

The effects of training on non-reading skills

Figure 18 illustrates the progress made by both intervention groups in the cognitive tasks, i.e. in phoneme deletion, vowel replacement, pseudoword repetition, selective attention and rapid automatized naming. In the phonological tasks, we calculated the number of correctly solved items per second, as a means to control the trade-off between speed and accuracy. We expected to find significant interaction effects, i.e. in case of the phonological tasks we suspected that the effect of time (increase of the scores) would be higher in the PNAVG than in the AVG group. In case of the visual selective attention task we also expected to find an interaction between group and time, i.e. a higher progress in the AVG group.

In case of phoneme deletion, we found that with time children increased the number of items solved per second ($F(1,50) = 17.96$, $p < .001$, $\eta^2 = 0.26$). We found no significant group effect ($F(1,50) = 0.01$, $p = .91$) or group and time interaction ($F(1,50) = 1.78$, $p = .19$). Similarly, we found a significant increase of scores with time in vowel replacement ($F(1,49) = 30.77$, $p < .001$, $\eta^2 = 0.39$), but no effect of group ($F(1,49) < 0.01$, $p = .97$) nor group and time interaction ($F(1,49) < 0.01$, $p = .99$). Also in pseudoword repetition we found an increase of scores with time ($F(1,52) = 15.53$, $p < .001$, $\eta^2 = 0.23$), but no significant effect of group ($F(1,52) = 0.01$, $p = .94$) or group and time interaction ($F(1,52) = 0.34$, $p = .56$).

We observed also an increase of selective visual attention ($F(1,44) = 96.56$, $p < .001$, $\eta^2 = 0.69$), but again neither group effect ($F(1,44) = 0.04$, $p = .94$) nor the interaction of group and time ($F(1,44) = 0.03$, $p = .86$) were significant. Finally, similar results were found for rapid automatized naming, were we obtained an increase of naming speed over time ($F(1,52) = 6.73$, $p = .01$, $\eta^2 = 0.12$), but no difference between the groups ($F(1,52) = 1.06$, $p = .31$) and no interaction of group and time ($F(1,52) = 2.60$, $p = .12$).

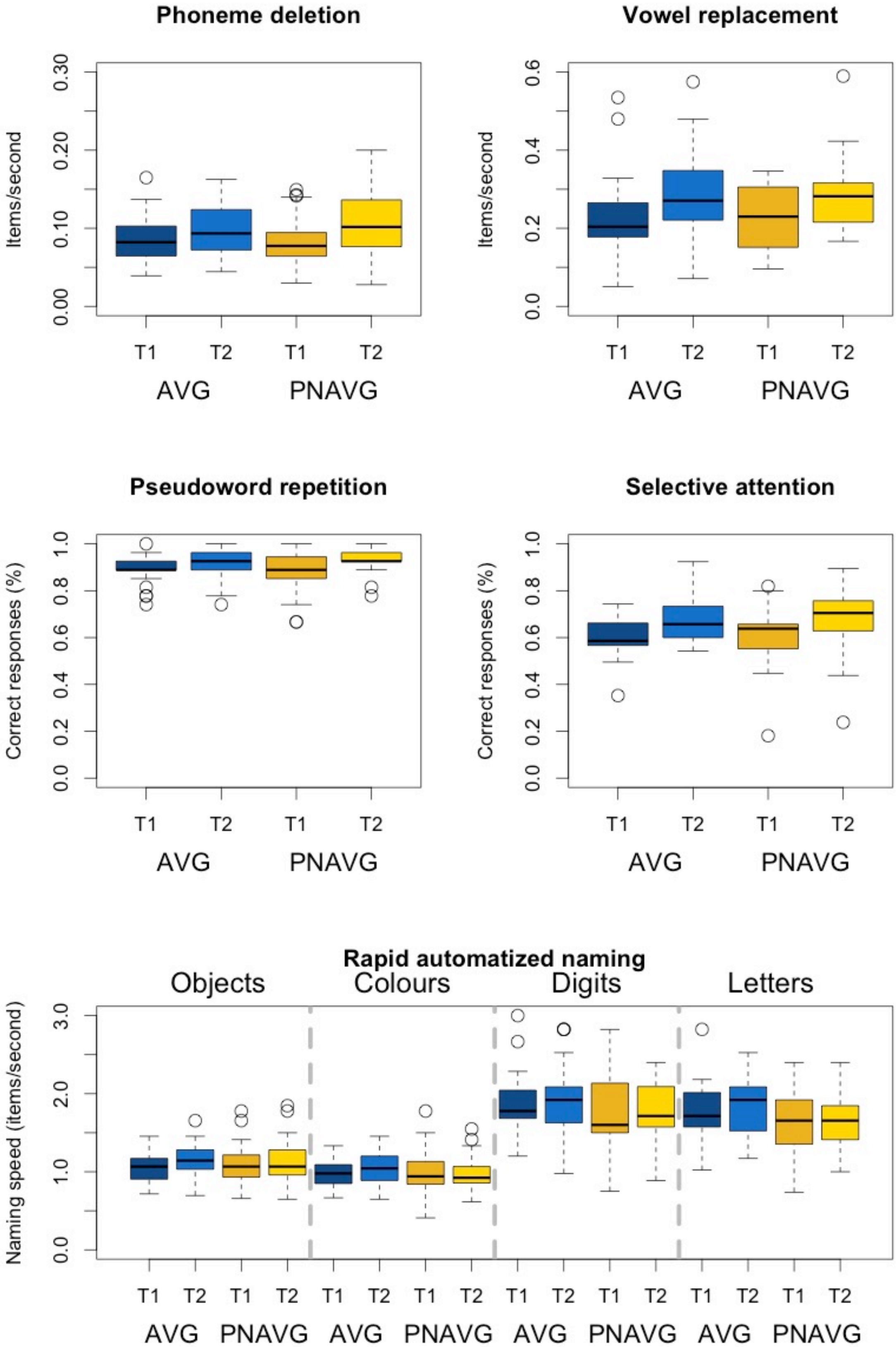

Figure 18. Scores in phonological, attention and rapid automatized naming tasks before and after the training in AVG (blue) and PNAVG (yellow) groups. In all measures, the increase of scores with time is significant, but there are no effects of group nor group and time interactions.

The effects of trainings related to the presence of phonological deficit

Before running the ANOVA models comparing the groups with and without a phonological deficit, we checked whether the phonological factor measured in Experiment 1a was still related to the phonological skills as measured in the pretest before the intervention. We found that the phonological factorial score was moderately related to the scores (items per second) in the phoneme deletion task used before the intervention ($r(50) = .50$, $p < .001$; see Figure 19), weakly related to the scores in pseudoword repetition task ($r(51) = .31$, $p = .02$), and not related to the vowel replacement scores (items per second; $r(49) = .15$, $p = .30$).

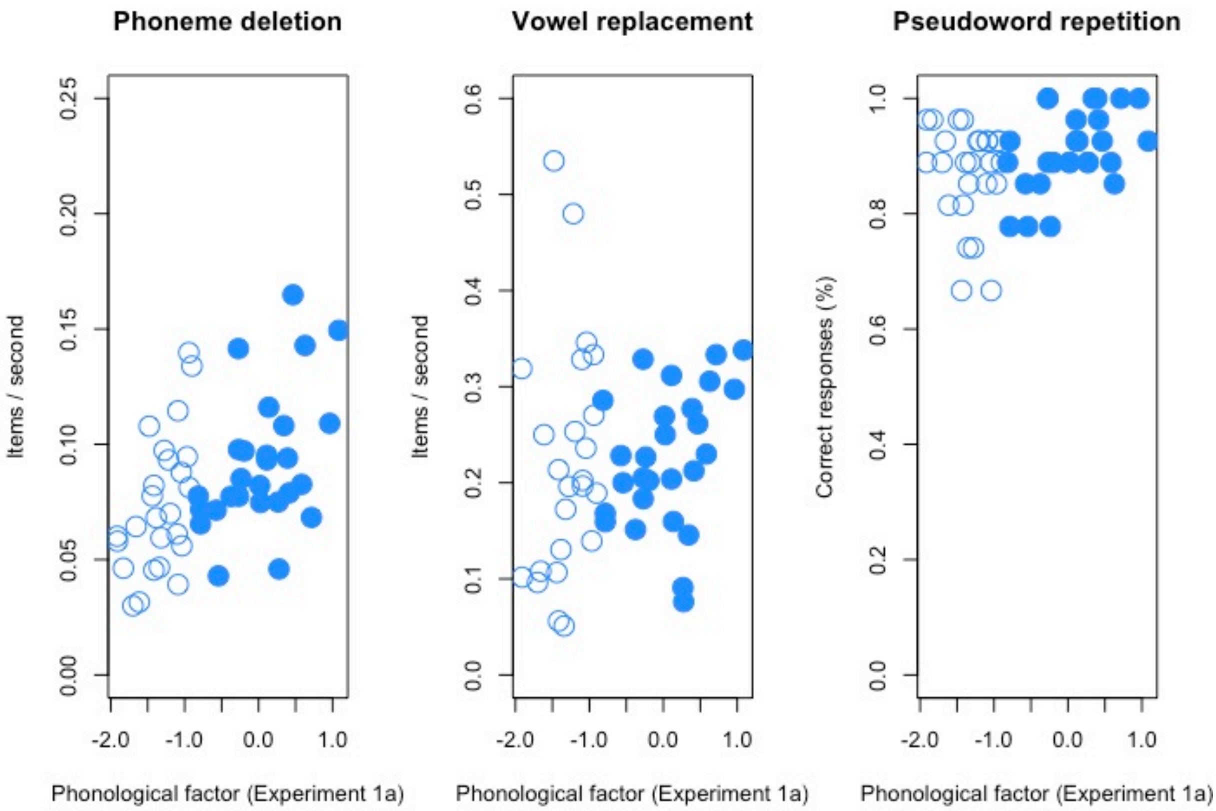

Figure 19. The scores in phonological tasks as assessed before the intervention in relation to the phonological factor measured a year earlier in dyslexic children with (blank circles) and without (full circles) a phonological deficit.

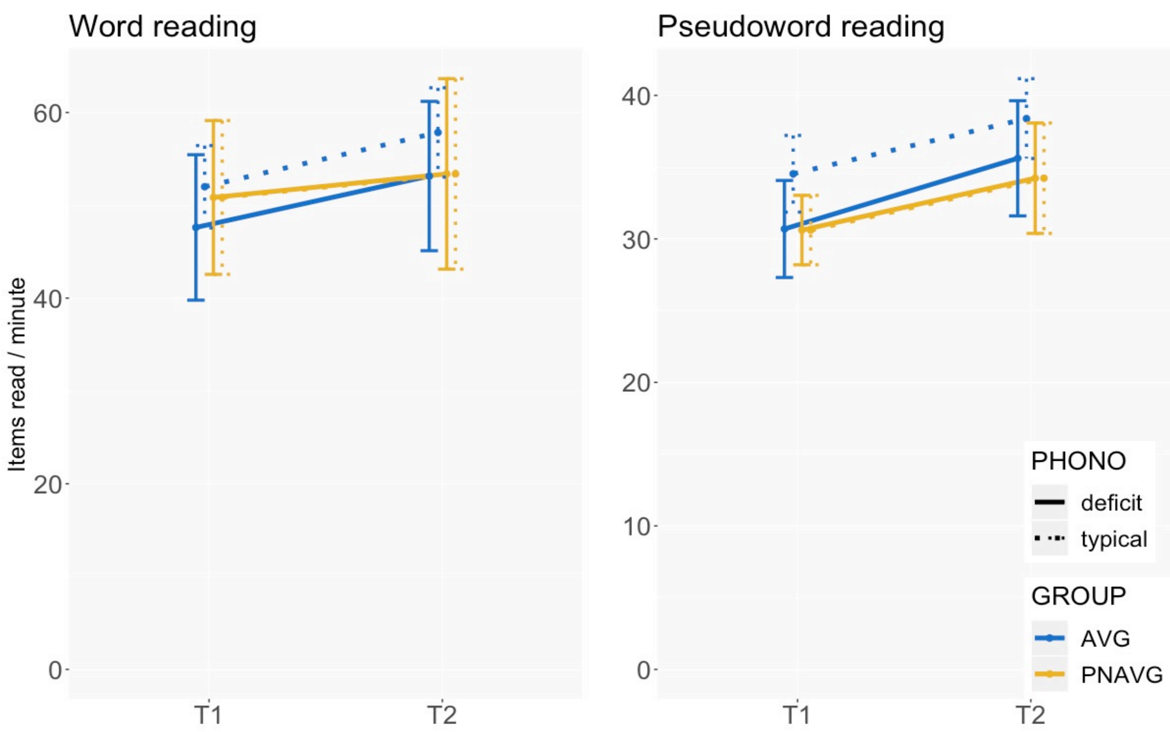

Figure 20. The increase of word and pseudoword reading in children with (solid line) and without (dotted line) a phonological deficit in AVG (blue) and PNAVG (yellow) groups. The error bars correspond to 95% CI.

In the ANOVA models we expected to find a three-way interaction of time, group (intervention type) and presence of the phonological deficit. In particular, we expected that the PNAVG (and not AVG) therapy would be specifically effective in children who had a phonological deficit, i.e. that the effect of the time would be especially visible in children with a phonological deficit who participated in the PNAVG programme.

For word reading (Figure 20) we found again significant effect of time ($F(1,49) = 25.98$, $p < .001$), but no effect of intervention type ($F(1,49) = 0.24$, $p = .63$) and no effect of phonological deficit ($F(1,49) = 0.02$, $p = .90$). We found no significant interaction of time, deficit and intervention ($F(1,49) = 2.25$, $p = .14$), and all other interactions were also insignificant. Similarly for pseudoword reading we found an increase of scores with time ($F(1,49) = 44.53$, $p < .001$) but no effect of intervention type ($F(1,49) = 0.85$, $p = .36$), no effect of phonological deficit (F(1,49) = 1.04, p = .31) and no interaction of time, deficit and intervention (F(1,49) = 1.07, p = .31.

Figure 21 illustrates the progress in phonological tasks in children with and without phonological deficit in both intervention programmes (AVG and PNAVG). For phoneme deletion we found a significant effect of time (F(1,46) = 18.68, p < .001). However we found no effects of intervention type (F(1,46) = 0.19, p = .66), of phonological deficit (F(1,46) = 3.82, p = .06) and no significant interactions (for time, intervention and phonological deficit F(1,46) = 2.25, p = .14). Similarly, in case of the vowel replacement task, we found an effect of time (F(1,46) = 33.78, p < .001), but no effects of intervention type (F(1,46) = 0.01, p = .92), phonological deficit (F(1,46) = 0.43, p = .52) and no interaction of the three variables (F(1,46 = 1.94, p = .17). Finally, for the pseudoword repetition, we found an effect of time (F(1,49) = 14.56, p < .001) with no effects of intervention type (F(1,49) = 0.01, p = .93), deficit (F(1,49) = 3.89, p = .05) and no interaction of the three variables (F(1,49) = 0.33, p = .57).

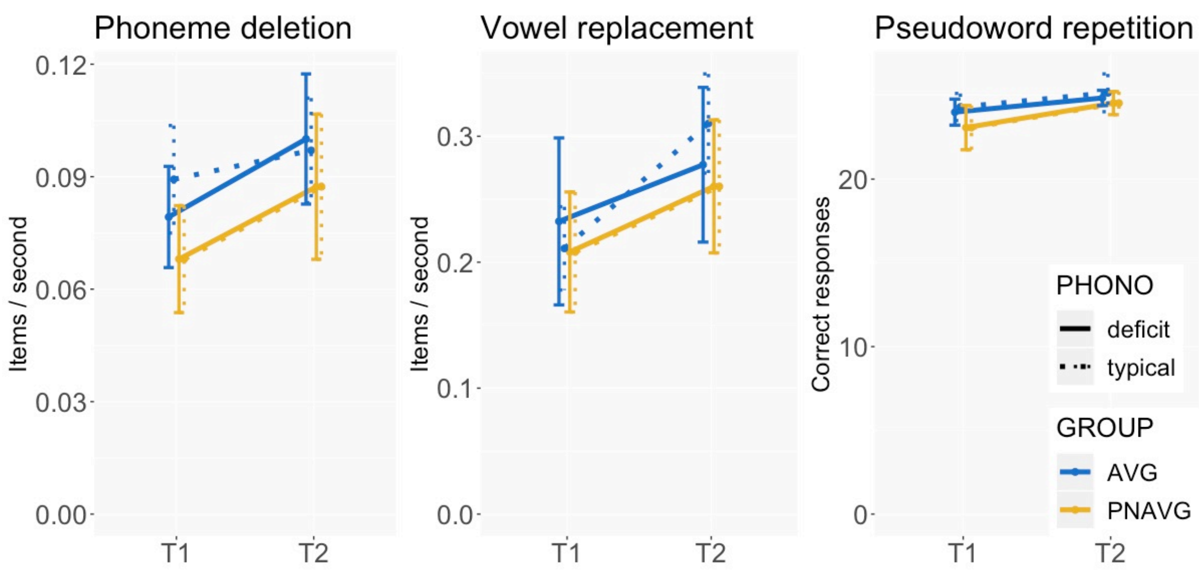

Figure 21. The phonological awareness in children with (solid line) and without (dotted line) a phonological deficit in AVG (blue) and PNAVG (yellow) groups. The error bars correspond to 95% CI.

Discussion

Typically children are eager to play computer games (Durkin, 2010; Primack et al., 2012), and therefore interventions based on playing video games may be a popular solution for reading difficulties. The previous studies showed that AVG may be effective in improving reading in children with dyslexia (Facoetti et al., 2017; Franceschini et al., 2013, 2017; Franceschini & Bertoni, 2019; Gori et al., 2013) and that phonological awareness may be also developed with the use of computer games (Mitchell & Fox, 2001; Segers & Verhoeven, 2004, 2005), and in this Chapter we aimed at replicating these results.

The previous studies on the effectiveness of video games showed that children who played AVG improved reading, whereas the level of reading in the group who played NAVG did not change (Franceschini et al., 2013, 2017; Gori et al., 2013). However, all the studies on AVG effectiveness suffered from serious methodological flaws, as these studies included very small groups of participants, varying between 18 (Franceschini & Bertoni, 2019) and 28 participants (Franceschini et al., 2017). Such limited sample size raises a possibility that the found effects results from a sampling error. In the Experiment 3, we used the same training method as in previous studies on AVG (Franceschini et al., 2013, 2017) with over two times bigger group (N = 54). This sample size gave us over 99% statistical power to find an effect of intervention of a previously reported size (Franceschini et al., 2013, 2017), as revealed with GPower (Faul et al., 2009). The previous results on effectiveness of phonological awareness trainings were much better documented, as they were replicated by several meta-analyses (Bus & van IJzendoorn, 1999; Ehri et al., 2001; Suggate, 2010, 2016). Therefore instead of traditional NAVG, we decided to include phonological non-action video games as a control to AVG.

We found that after both interventions participants could read more words and pseudowords per minute (Figure 17). However, there was no difference between the two groups in reading skills or in the progress in reading. What is even more important, is that the increase of reading level in the two intervention group did not differ from the progress made by a dyslexic control group who did not participate in any intervention (Figure 16). This suggests that the improvement observed in the intervention groups resulted from the repeated measurement, a task learning effect, regular development or schooling rather than from real effectiveness of applied methods. This outcome questions the previous reports on effectiveness of AVG interventions. On the other hand, there are also other plausible explanations of the lack of difference between the control group and the participants of the interventions, as the web-based may be less reliable than direct measurement of reading skills (Peters et al., 2019). Perhaps, if the control group was assessed directly with the use of the same tasks as the training groups, we would find a higher increase of reading scores in the interventions' participants.

The participants of the two interventions improved not only reading, but also all other measured skills, such as phonological awareness, phonological working memory, visual selective attention and rapid automatized naming (see Figure 18). We initially assumed to observe increase of skills specific for the trained abilities, such as enhancement of phonological awareness in PNAVG and boost of visual attention in AVG group. Contrary to our expectations, the found effects were non-specific: the increase of scores was present in both intervention groups to the same extent. Although previous studies showed that playing AVG may improve phonological skills (Facoetti et al., 2017), the more plausible interpretation of these results is that the observed progress reflects the test practice effect, especially as we noted also an increase of rapid automatized naming, a skill particularly difficult to train (de Jong & Vrielink, 2004). In the Experiment 3, the time between the two testings was on average 46 days, which is both short enough for participants to still remember the tasks, and long enough to develop skills. Although the exact reading and phonological tasks used in the two testing sessions employed different items (Appendix 5), the testing procedure was the same. Perhaps, participants could remember the used tasks and employed better strategies of solving them during the second testing.

We also found that the PNAVG and AVG have the same impact on reading and phonological progress in children with and without phonological deficit (Figures 20 and 21). In other words, even in a group of children with previous phonological difficulties PNAVG and AVG led to the same increase of reading and phonological skills. The phonological deficits, as defined in the Experiment 1a, seemed to be quite stable over time (Figure 19), as the phonological factor (measured one year earlier) was moderately strongly related to phonological awareness (assessed with a phoneme deletion task) even after a year.

We found the two interventions to be ineffective in terms of their impact on the domain-specific skills, as well as their impact on reading abilities. The ineffectiveness of the interventions may be justified in several ways, which concern both the training procedure and the groups of participants. The AVG intervention was based on exactly the same games as in the previous research (Franceschini et al., 2013, 2017), but we used another form of playing. In the previous studies, children played the games on a Wii console with a remote controller during individual training sessions. Instead we used regular notebooks and computer mouses, at this type of equipment is more common in households. This difference could potentially affect the results, as previously used AVG trainings involved body movement during the play, while in the current study children were seated without movement. On the other hand, if the progress in reading in the previous studies resulted from the motor component, it should be also visible in NAVG players who used the same equipment for playing. The previous trainings had also different intensity than the one employed in the current study, as they lasted for two weeks and included nine 80-minute-long sessions (720 minutes in total), whereas the trainings used in the current study were less condensed and consisted of 16 sessions of 50 minutes (800 minutes in total) in four weeks. Perhaps, similarly as in the case of phonological awareness training (Ehri et al., 2001) there is an optimal length of intervention based on AVG. However, it is rather impossible that the range of optimal duration of AVG intervention would include 12 hours (720 minutes) but not 80 minutes more, as in the case of phonological awareness intervention this range is quite wide (5 to 18 hours, (Ehri et al., 2001)). Finally, we applied an assessment of visual selective attention which did not resemble the training, as it did not involve any aspects of action games. On the other hand, previous studies showed that playing AVG may improve also visual selective attention as measured with similar tasks (Bavelier et al., 2012; Green & Bavelier, 2012).

The lack of effects of the phonological awareness training is even more surprising, as previous research has been very consistent about the effectiveness of phonological interventions in dyslexia (Bus & van IJzendoorn, 1999; Ehri et al., 2001; Suggate, 2010). There are several possible explanations of the ineffectiveness of PNAVG used in the current study. First of all, the majority of the games employed in the PNAVG intervention were purely phonological, i.e. they were based only on processing of sound without any reading-relate component (see Appendix 4). As shown by previous meta-analyses, phonological awareness trainings are particularly effective if they use letter material in addition to pure phonological stimuli (Bus & van IJzendoorn, 1999; Ehri et al., 2001) and perhaps inclusion of some reading-related material would enhance the effectiveness of the PNAVG. Second, our PNAVG intervention included training of many different phonological skills such as alliteration, phoneme and syllable deletion, phoneme and syllable blending and rhyming), while trainings of a single phonological awareness skill may be more beneficial (Ehri et al., 2001). In the PNAVG programme we included various tasks in order to make the games more entertaining and less boring, however perhaps focusing on phonological skills only closely related to reading (such as phoneme blending) and based on phonemes (and not syllables) could be more effective (National Institute of Child Health and Human Development, 2000; Solity et al., 2000). Third, as children were playing games in the same room, we decided to include rather passive (mouse clicking) than active (oral) responses in the games. Perhaps tasks in which participants would be required to pronounce the responses would be more demanding and result in a higher boost of phonological skills. Finally, although the tasks training in the PNAVG intervention were passive, we used measures of active phonological awareness in the testing sessions. It is possible that using of a particular tasks employed in the games in assessment of phonological awareness would results in a higher increase of the specific phonological skill.

In addition to the properties of the applied interventions, there are also some participants' characteristics which could decrease the effectiveness of the trainings. First of all, the participants were relatively experienced readers, despite their dyslexia, as they were attending at least the third grade of primary school. Perhaps the interventions would be more effective in younger children at the very beginning of formal education, as phonological awareness interventions have been shown to be particularly beneficial in groups of preschool children (Bus & van IJzendoorn, 1999; Ehri et al., 2001; Schneider et al., 1999; Suggate, 2010). On the other hand, the previous participants of the AVG trainings were of similar age or only slightly younger (average around 10 years; Franceschini et al., 2013, 2017; Franceschini & Bertoni, 2019) than participants of the Experiment 3 (average around 11 years).

To summarize, neither AVG nor phonological NAVG were found to be an effective intervention for Polish children with dyslexia. These trainings were ineffective in terms of both, their impact on reading skills, as well as their impact on the trained skills, even in children with deficits in the trained domains. Therefore we conclude that not only finding a far transfer from the skills employed in the training to reading is impossible, but also a close transfer to another skill of the same domain may be difficult with an intervention based on computer games.

Chapter 9. Visual ad-hoc treatment: Experiment 4

In Chapter 8 we described an attempt to increase reading skills of children with dyslexia in two intervention programmes based either on phonological awareness training or on action video games. As reported in Chapter 8, the trainings in Experiment 3 lasted for four weeks, and each participant spent over 13 hours on playing the games, but the intervention was not effective. One of the possible reasons of the ineffectiveness of the trainings was the fact that the trainings were not performed individually as in previous research on action video games (Franceschini et al., 2013, 2017). On the other hand, individual therapies are often very expensive, in terms of the salaries of the specialists, paid either by the governments or by parents of children attending the trainings.

As reviewed in the last section of Chapter 4, there are some ad hoc possibilities of improving reading in children with dyslexia, which are, by definition less expensive, faster and easier to introduce than long-term trainings. However, despite the initial promising results of increasing inter-letter spaces (Zorzi et al., 2012), further research in this topic brought inconsistent results, and on the basis of the existing literature it is impossible to predict whether extra-large inter-letter spacing may enhance reading in Polish children with dyslexia. It is however worth mentioning that if indeed texts with increased inter-letter spacing are read by children with dyslexia faster and/or more accurately, this result may have wide practical implications, as increased spacing may be easily introduced on webpages and digital book readers.

In the Experiment 4, we aimed to resolve the inconsistencies in the research on inter-letter spacing. To achieve this goal, we invited to a study a higher number of children than in the majority of the previous studies (Duranovic et al., 2018; Hakvoort et al., 2017; Martelli et al., 2009; Masulli et al., 2018; Perea et al., 2012; Sjoblom et al., 2016; Zorzi et al., 2012). The Experiment 4 was based on natural sentence-reading paradigm, in which we assessed the impact of increased and decreased inter-letter spacing on several reading measures such as accuracy, speed, level of comprehension, and number and duration of fixations. The same procedure was applied in typical and dyslexic readers, and additionally we compared the level of comprehension, as well as the number and duration of fixations between oral and silent reading. Such comparison has not been included in any of the previous studies, which mostly employed only oral reading (Dotan & Katzir, 2018; Duranovic et al., 2018; Hakvoort et al., 2017; Masulli et al., 2018; Sjoblom et al., 2016; Zorzi et al., 2012). In addition to regular and extra-spaced conditions, we included a condensed conditions, as even less is known about the impact of decreased inter-letter spacing on reading in children (Slattery et al., 2016; Slattery & Rayner, 2013)

Research questions

The most important research question in the Experiment 4 was whether increased inter-letter spacing can enhance reading in children with dyslexia and lead to similar reading performance in typical and dyslexic readers. We assumed that increased inter-letter spacing would result in a higher accuracy, reading speed and level of comprehension, as well as lower number of fixations, and shorter fixation durations for dyslexic children as compared to regular spacing. In other words, we hypothesized that increasing inter-letter spacing would make reading performance of children with dyslexia approach that of typical readers.

On the other hand, in typical readers, we suspected no particular gain from increased-spacing and a decrease in reading measures in the condensed condition (Montani et al., 2015), which would make their reading performance more similar to that of children with dyslexia.

Finally, we expected that silent reading, as compared to oral reading, would results in lower comprehension scores (Kragler, 1995) fewer and shortened fixations (Vorstius et al., 2014).

Method

Participants

We recruited 75 participants of the Experiment 1a. As the study was performed about two years after the Experiment 1a, the participants were already 10 to 14 years old (*M* = 12.17, *SD* = 1.06). The sample included 30 girls and 45 boys. The same criteria as described in the Experiment 1a were applied for dyslexia diagnosis, and the group included 37 typical readers and 38 children with dyslexia. The groups of dyslexic and typical readers did not differ in age, sex, nonverbal IQ, or parental education. However, there were substantial differences between the groups in all measures of reading, writing and phonological skills (Table 15).

Procedure

Participants were asked to read sentences either silently (first 48 sentences) or orally (last 45 sentences). The first three items were used for training. After reading each sentence, participants were asked to press the space button (see Figure 22). Then participants selected one of four pictures corresponding to the read sentence by pressing a button on the numeric keyboard. Reading time was not limited. The whole experiment took between 15 and 63 minutes (*M* = 27.93, *SD* = 10.82). The procedure was implemented in Tobii Studio version 3.4.5.

Apparatus

The data on eye movements, i.e. the information about the location and duration of the participants' gaze fixations, was recorded with an infrared-based eye-tracking system (Tobii TX 300), integrated with a 23-inch screen (with screen resolution 1920 × 1080 pixel). The Tobii TX300 has a temporal resolution of 3 ms (sampling rate 300 Hz), gaze accuracy (average difference between the actual stimuli position and the measured gaze position) of 0.4° – 0.9°, and precision (average difference between the measurements of the same gaze position) of 0.04° – 0.15°, depending on gaze angle and lighting, as stated in Tobii TX300 manual. Participants were seated around 60 – 65 cm from the screen, which is within the optimal range for recording described in the Tobii TX300 manual. The data from both eyes were recorded and analyzed. To reduce the noise inherent in each measure, measurements from both eyes were averaged. We used Tobii Studio's 9-point automated calibration tool, which presents a dot that expands and contracts at nine fixed locations on the screen. Participants were instructed to look at the dots without moving their heads.

Table 15. Typical readers and children with dyslexia in Experiment 4.

	Typical readers (***n*** **= 37)**	**Dyslexic readers** (***n*** **= 38)**	
Sex	17 girls 20 boys	13 girls 25 boys	$X^2(1) = 1.08, p = .300$
Age (years)	12.18 (1.18) [11.80; 12.56]	12.17 (0.95) [11.87; 12.47]	$t(73) = 0.03, p = .980$ d < 0.01
Nonverbal IQ (WISCR)	117.54 (12.97) [113.36; 121.72]	113.92 (10.74) [110.51; 117.33]	$t(73) = 1.32, p = .192$ $d = 0.30$
Maternal education (years)	17.72 (2.69) [16.85; 18.59]	17.22 (3.67) [16.05; 18.39]	$t(73) = 0.23, p = .819$ $d = 0.16$
Paternal education (years)	16.87 (3.04) [15.89; 17.85]	16.25 (3.35) [15.18; 17.32]	$t(73) = 0.20, p = .842$ $d = 0.19$
Word reading accuracy [a]	6.19 (1.81) [5.61; 6.77]	3.18 (1.29) [2.77; 3.59]	$t(73) = 8.30, p < .001$*** $d = 1.92$
Pseudo-word reading speed [a]	5.68 (1.89) [5.07; 6.29]	2.82 (1.09) [2.47; 3.17]	$t(73) = 8.07, p < .001$*** $d = 1.85$
Reading with lexical decision speed [a]	6.03 (1.82) [5.44; 6.62]	3.05 (1.77) [2.49; 3.61]	$t(73) = 7.18, p < .001$*** $d = 1.66$
Text reading speed [a]	6.23 (2.51) [5.42; 7.04]	2.76 (1.25) [2.36; 3.16]	$t(37) = 5.21, p < .001$*** $d = 1.75$
Writing to dictation accuracy [a]	5.43 (2.14) [4.74; 6.12]	2.47 (1.41) [2.02; 2.92]	$t(73) = 7.09, p < .001$*** $d = 1.63$
Word spelling accuracy [a]	4.82 (2.42) [4.04; 5.60]	2.41 (1.54) [1.92; 2.90]	$t(37) = 3.57, p = .001$** $d = 1.19$
Phoneme deletion accuracy [a]	5.73 (2.13) [5.04; 6.42]	3.82 (1.67) [3.29; 4.35]	$t(73) = 4.33, p < .001$*** $d = 1.00$
Battery of phonological tasks accuracy [a]	4.95 (1.91) [4.33; 5.57]	3.24 (1.84) [2.65; 3.83]	$t(73) = 3.95, p < .001$*** $d = 0.91$
Pseudo-word repetition accuracy [a]	5.16 (1.94) [4.53; 5.79]	3.58 (1.97) [2.95; 4.21]	$t(73) = 3.51, p = .001$** $d = 0.81$

Note: *** - $p < .001$, ** - $p < .01$, * - $p < .05$ Mean (SD) [95% CI].
[a] Standard ten scores (sten) are reported. Population mean equals 5.5 (2.0).

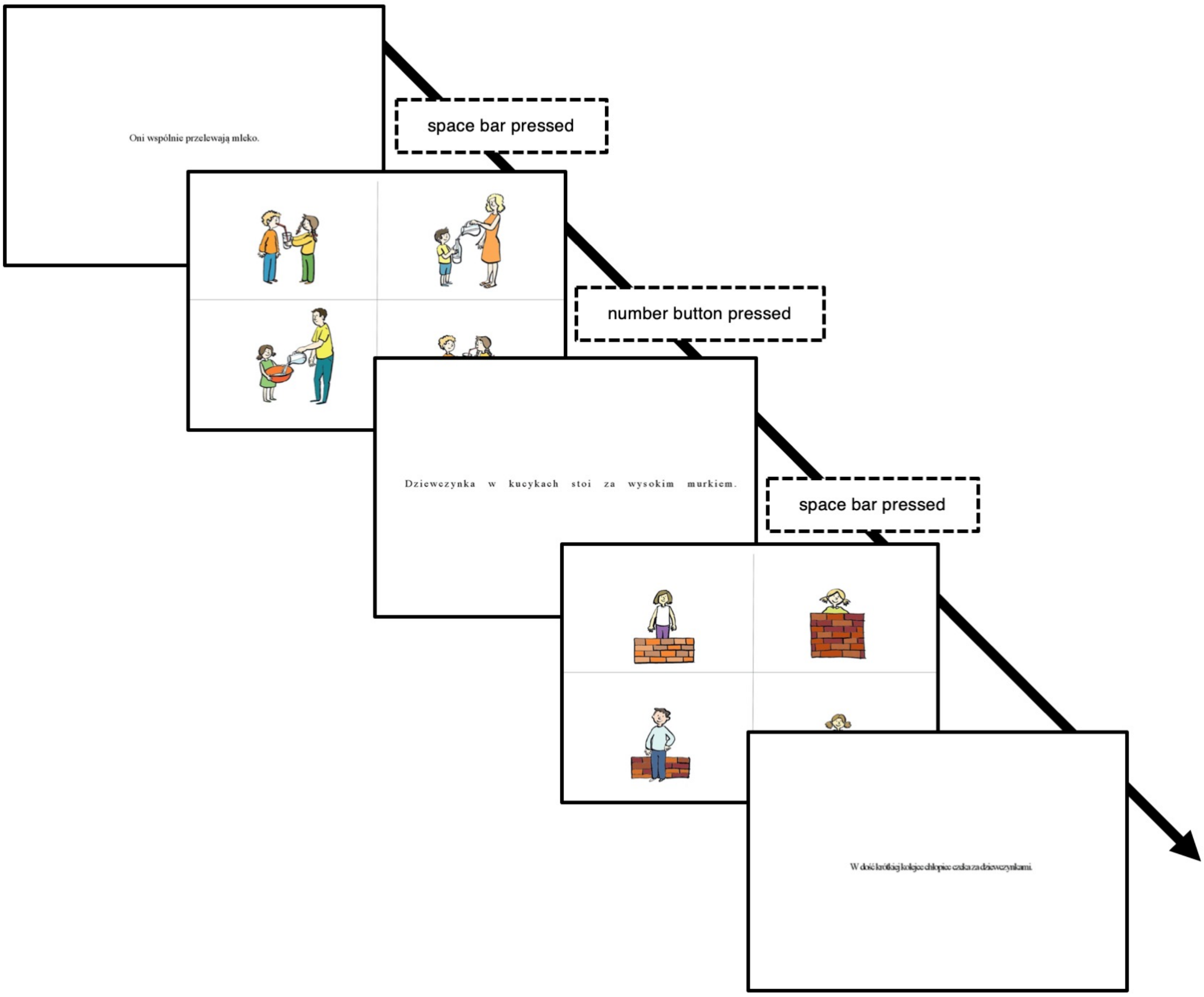

Figure 22. The design of the Experiment 4. The sentences in the regular, spaced and condensed conditions were mixed. Each sentence was followed by a picture board.

Materials

The materials included 93 short meaningful sentences. The sentences resembled the stimuli used in a test of grammar comprehension (Smoczyńska, Haman, et al., 2015). Some of the sentences were modified in order to make them more difficult to comprehend. This manipulation was provided to limit the ceiling effect in comprehension in the typically reading group. The exact list of the stimuli, along with information on their difficulty is available in the Appendix 8. The first three training sentences were not included in the analyses, and the analyses included the remaining 90 sentences.

The sentences were presented either in one of three conditions: a regular condition (Times New Roman, 16 pts), a spaced condition (+2.5 inter-letter spacing with words separated by three space characters; (Smoczyńska, Haman, et al., 2015; Zorzi et al., 2012)), or in condensed condition (-1.5 inter-letter spacing; (Montani et al., 2015)). The sentences were written in black color on a white background and were followed by pictures illustrating either the target sentence, or similar sentences. The pictures were adapted from therapeutic materials designed for speech and language specialists treating language impairments (Smoczyńska, Kochańska, et al., 2015).

The sentences were not presented in blocks of the same condition. Instead, sentences representing different conditions were mixed, and the number of subsequent sentences in the same condition was limited to four (see column Condition in the set A in the Appendix 9). The stimuli were presented in one of three sets (A, B, C) which differed in assignment of the sentences to one of three conditions: normal, spaced, and condensed. The sentences which were printed in regular condition in set A, where spaced in set B, and condensed in set C, etc. Each sentence appeared roughly the same number of times printed in normal, large, and small spacing, and each child read each sentence just once. In order to minimize the effect of fatigue on the collected data, half of the participants saw the stimuli in a reversed order.

The stimuli in the three sets were matched in terms of length (Table 16). We assessed the level of the difficulty of the stimuli with the use of Jasnopis application (Dębowski et al., 2015), an online tool designed for the assessment of readability of Polish texts. Namely, we used the level of text difficulty as a measure of readability of the stimuli. The Jasnopis application classified each of the typed sentences to one of the seven levels varying from 1: easy texts appropriate for children starting education, to 7: difficult texts comprehendible only for specialists (Dębowski et al., 2015). The difficulty of the sentences varied between 2.88 and 4.99, which corresponds to texts of moderate difficulty for children. These scores were satisfactory, as our aim was to prepare stimuli which could vary in the level of comprehension among the typically reading children. The difficulty of the stimuli did not differ between the three sets (A, B and C; see Table 16).

Table 16. Characteristics of the stimuli across three sets in Experiment 4.

	Set A	Set B	Set C	
Sentence length (in words)	9.87 (2.71) [8.90, 10.84]	9.67 (2.59) [8.74, 10.59]	9.80 (3.01) [8.72, 10.88]	$F(2,87) = 0.04$, $p = .96$
Sentence length (in characters)	61.87 (17.95) [55.44, 68.29]	61.87 (14.61) [56.64, 67.1]	61.93 (19.49) [54.96, 68.91]	$F(2,87) = 0.00$, $p = 1.00$
Sentence length (in syllables)	22.27 (6.86) [19.81, 24.72]	22.20 (5.33) [20.29, 24.11]	21.90 (6.98) [19.4, 24.40]	$F(2,87) = 0.03$, $p = .97$
Level of difficulty	3.60 (2.01) [2.88, 4.32]	4.37 (1.75) [3.74, 4.99]	3.87 (1.78) [3.23, 4.50]	$F(2,87) = 1.33$, $p = .27$

Note: The range of the level of difficulty was 1 to 7, meaning the educational level necessary to understand the text (1: grades 1-3 of primary school, 7: PhD in a given discipline). Mean (SD) [95% CI].

Data Analyses

We measured several variables for each child and each sentence. For both oral and silent reading, we measured (1) level of reading comprehension, i.e. whether the participant selected the picture correctly, (2) fixation duration on the words in the sentence, (3) number of fixations on the words. For the oral reading, we additionally analyzed the recordings and assessed (4) reading accuracy and (5) reading speed. Reading accuracy was assessed with the number of errors committed while oral reading. In particular, we calculated the number of incorrectly read words. A word was assigned as incorrectly read if there was a difference between the read form and the target one, such as missed, added or replaced phoneme(s). Reading speed was calculated in words per minute, on the basis of reading time for each sentence separately. The number of words in the sentence was divided by the reading time of the sentence (in minutes).

We excluded from eye-tracking analyses the participants whose eye-tracking data were recorded for less than 90% of trials. Such data loss happened because of some calibration errors or significant head movements during the assessment. Therefore we analyzed eye-tracking data from 63 children of which 33 were typical readers and 30 were participants with dyslexia. No children were excluded from reading accuracy, speed, or comprehension analyses so we analyzed the whole set of collected data from 75 participants.

Statistical Analyses

In order to enhance the results comparability with the previous papers (Hakvoort et al., 2017; Sjoblom et al., 2016; Slattery & Rayner, 2013; Zorzi et al., 2012) we applied a series of ANOVA models. The R (R Core Team, 2019) scripts used for the data analyses and visualization are presented in the Appendix 9. We ran a series of two-way or three-way ANOVAs with repeated measures in R studio with a significance level of $\alpha = 0.05$ using the 'aov' function. We also calculated generalized eta squared (Bakeman, 2005) effect sizes for each main effect with the use of the 'ezANOVA' package (Lawrence, 2016). In all analyses, we included the group (typical readers versus children with dyslexia) as a between-subject factor and the spacing condition (regular vs spaced vs condensed) as a within-subject factor, similar to previous research on inter-letter spacing (Hakvoort et al., 2017; Zorzi et al., 2012). In case of reading comprehension, duration of fixations and number of fixations, we additionally included the reading mode (silent vs oral) as a within subject-factor. In case of significant effects in the ANOVA model, we run a Tukey's Honest Significant Difference test in order to explore the effects. The analyses of reading comprehension and number and duration of fixations were run for all 90 items (both read silently and orally). The analyses of reading accuracy and reading speed were run for sentences read orally ($n = 45$).

Results

The results are presented on the Figure 23 and in the Table 17.

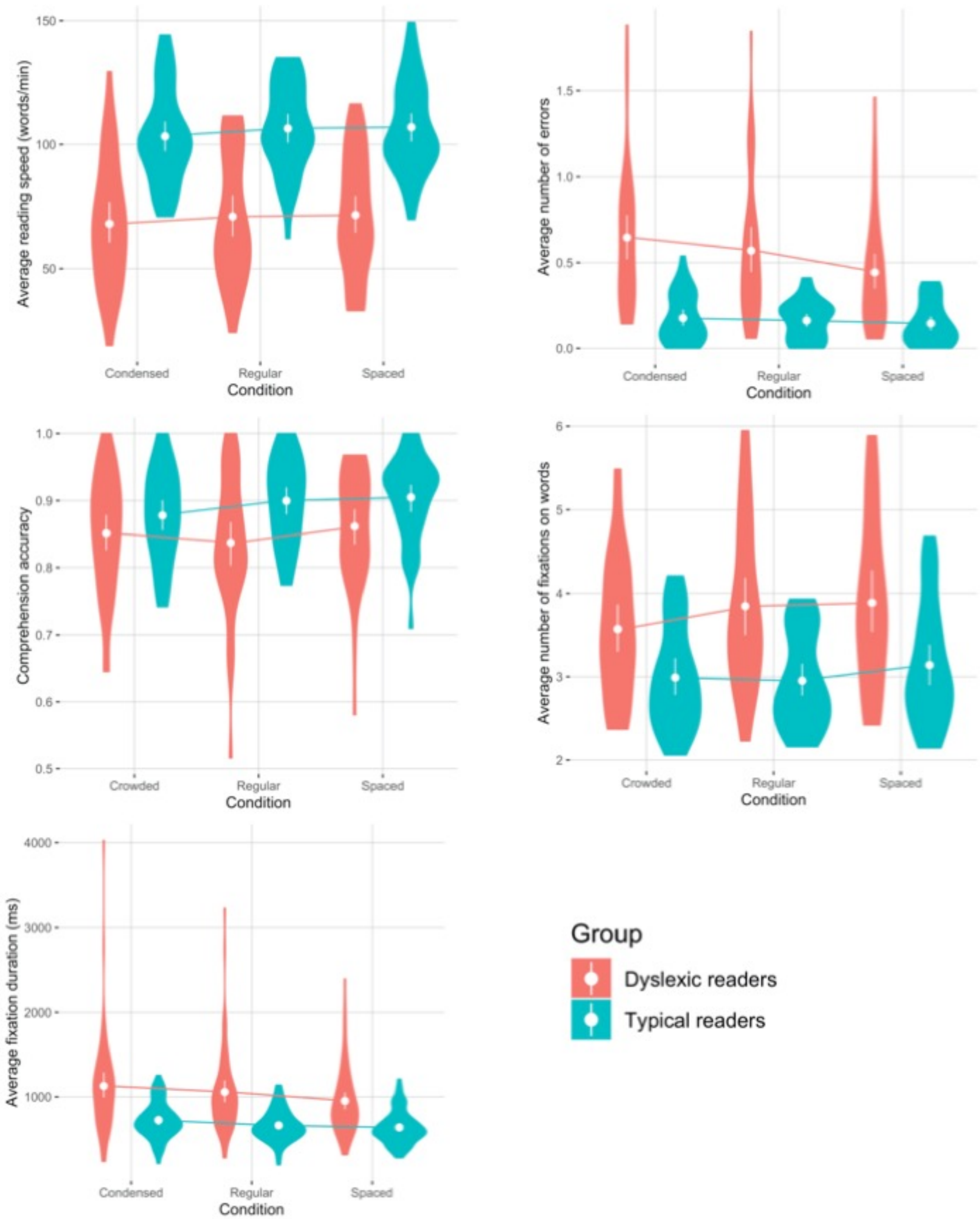

Figure 23. The scores of dyslexic (pink) and typical (green) readers across condensed, regular and spaced conditions.

In case of reading speed we found a large significant main effect of group ($F(1,73) = 52.25$, $p < .001$, $\eta_G^2 = .399$): typical readers were significantly faster than dyslexic readers. We found a small significant main effect of condition ($F(2,146) = 5.43$, $p = .005$, $\eta_G^2 = .005$). A Tukey's Honest Significant Difference test revealed that the reading speed in the condensed condition was lower than in the regular ($p = .029$) and spaced ($p = .007$) conditions, and there was no difference between regular and spaced conditions ($p = .882$). We found no interaction of group and condition ($F(2,146) = 0.01$, $p = .994$, $\eta_G^2 < .001$).

For reading accuracy, we found a large significant main effect of group ($F(1,73) = 44.64$, $p < .001$, $\eta_G^2 = .315$): typical readers were significantly more accurate than dyslexic readers. We found a small significant main effect of condition ($F(2,146) = 8.37$, $p < .001$, $\eta_G^2 = .028$). A Tukey's Honest Significant Difference test revealed that the spaced condition generally resulted in higher reading accuracy than condensed ($p < .001$) and regular ($p = .039$) conditions. There was no difference between condensed and regular conditions ($p = .270$). We found a small significant interaction between group and condition ($F(2,146) = 4.49$, $p = .013$, $\eta_G^2 = 0.015$). A Tukey's Honest Significant Difference test revealed significant differences between spaced and regular ($p = .027$) and between spaced and condensed ($p < .001$) conditions in the dyslexic group. Reading accuracy did not differ significantly between the condensed and regular conditions in the dyslexic group ($p = .430$). There were no significant differences between conditions in typical readers (all p-values $> .976$). Independent of condition, dyslexic readers had lower reading accuracy than typical readers (p-values $< .001$).

For text comprehension, we found a small significant main effect of group ($F(1,73) = 9.20$, $p = .003$, $\eta_G^2 = 0.048$): typical readers understood significantly more sentences than dyslexic readers. We found no effect of condition ($F(2,146) = 2.33$, $p = .101$, $\eta_G^2 = 0.008$) and no interaction between group and condition ($F(2,146) = 0.97$, $p = .383$, $\eta_G^2 = 0.003$). We found a small significant effect of the reading mode ($F(1,73) = 4.02$, $p = .049$, $\eta_G^2 = 0.008$): sentences read orally were more often comprehended.

For number of fixations, we found a medium-size significant main effect of group ($F(1,69) = 17.67$, $p < .001$, $\eta_G^2 = 0.165$): dyslexic readers had significantly more fixations than typical readers. We found a small significant main effect of condition ($F(2,138) = 9.56$, $p < .001$, $\eta_G^2 = 0.011$). A Tukey's Honest Significant Difference test revealed that the spaced condition resulted in a higher number of fixations than the condensed condition ($p < .001$) and the regular condition ($p = .008$). There was no difference between the regular and the condensed conditions ($p = .422$). We found no effect of the reading mode ($F(1,69) = 3.80$, $p = .055$, $\eta_G^2 = 0.005$) and no interaction between the group and the condition ($F(2,138) = 1.47$, $p = .233$, $\eta_G^2 = 0.002$).

For duration of fixations, we found a medium-size significant main effect of group ($F(1,59) = 16.78$, $p < .001$, $\eta_G^2 = 0.195$): typical readers had significantly shorter fixations than dyslexic readers. We found a small significant main effect of condition ($F(2,118) = 21.89$, $p < .001$, $\eta_G^2 = 0.019$). A Tukey's Honest Significant Difference test revealed that the condensed condition resulted in longer fixations than regular ($p = .003$) and spaced conditions ($p < 0.001$), and spaced conditions resulted in shorter fixations than regular conditions ($p = .003$). We found no effect of the reading mode ($F(1,59) = 0.05$, $p = .823$, $\eta_G^2 < 0.001$) and no interaction between the group and the condition ($F(2,118) = 3.06$, $p = .051$, $\eta_G^2 = 0.002$).

Table 17. Reading performance typical readers and children with dyslexia across three conditions and two modes in Experiment 4.

Reading speed (words per minute)			
	Condition	**Dyslexic readers** (***n*** **= 38)**	**Typical readers** (***n*** **= 37)**
	Condensed	68.07 (25.08) [35.23; 100.91]	103.28 (19.33) [97.05; 109.51]
	Regular	71.00 (25.29) [37.15; 104.85]	106.46 (17.83) [100.71; 112.21]
	Spaced	71.60 (24.25) [37.58; 105.62]	106.99 (18.43) [101.05; 112.93]
Number of errors in a sentence			
	Condition	**Dyslexic readers** (***n*** **= 38)**	**Typical readers** (***n*** **= 37)**
	Condensed	0.65 (0.41) [0.59; 0.71]	0.18 (0.14) [0.13; 0.23]
	Regular	0.57 (0.42) [0.52; 0.62]	0.16 (0.12) [0.12; 0.20]
	Spaced	0.44 (0.34) [0.39; 0.49]	0.15 (0.13) [0.11; 0.19]
Percent of correctly comprehended sentences			
Mode	**Condition**	**Dyslexic readers** (***n*** **= 38)**	**Typical readers** (***n*** **= 37)**
Oral	Condensed	0.86 (0.11) [0.83; 0.90]	0.89 (0.08) [0.87; 0.93]
	Regular	0.86 (0.12) [0.82; 0.89]	0.90 (0.08) [0.87; 0.93]
	Spaced	0.87 (0.10) [0.84; 0.90]	0.93 (0.08) [0.90; 0.95]
Silent	Condensed	0.84 (0.11) [0.81; 0.88]	0.87 (0.09) [0.84; 0.90]
	Regular	0.83 (0.13) [0.79; 0.87]	0.90 (0.08) [0.87; 0.93]
	Spaced	0.86 (0.12) [0.82; 0.90]	0.90 (0.09) [0.87; 0.93]
Number of fixations per word			
Mode	**Condition**	**Dyslexic readers** (***n*** **= 30)**	**Typical readers(*n*** **= 33)**
Oral	Condensed	3.47 (0.89) [3.15; 3.79]	2.84 (0.59) [2.64; 3.04]
	Regular	3.61 (0.95) [3.27; 3.95]	2.82 (0.59) [2.62; 3.02]
	Spaced	3.73 (1.09) [3.33; 4.12]	3.04 (0.74) [2.79; 3.29]
Silent	Condensed	3.65 (1.03) [3.28; 4.02]	2.92 (0.85) [2.63; 3.21]
	Regular	3.79 (1.16) [3.38; 4.21]	2.91 (0.74) [2.65; 3.16]
	Spaced	3.97 (1.06) [3.59; 4.35]	3.01 (0.84) [2.73; 3.30]
Duration of fixations on words (miliseconds)			
Mode	**Condition**	**Dyslexic readers** (***n*** **= 30)**	**Typical readers** (***n*** **= 33)**
Oral	Condensed	1112 (668) [1048; 1177]	731 (189) [533; 928]
	Regular	1050 (552) [983; 1116]	674 (194) [540; 808]
	Spaced	919 (375) [852; 986]	660 (197) [483; 837]
Silent	Condensed	1137 (495) [1052; 1222]	720 (249) [548; 892]
	Regular	1068 (482) [1005; 1131]	652 (184) [491; 812]
	Spaced	990 (448) [922; 1059]	617 (200) [617; 617]

Note: Mean (SD) [95% CI].

Discussion

The results of the Experiment 4 are summarized in the Table 18. In all measures we found that typical readers performed higher than children with dyslexia: they read faster and made fewer errors in reading, presented a slightly higher level of comprehension, and made fewer fiations for a shorter time. All these effects could have been expected, as low reading speed and accuracy are typical in Polish children with reading impairment (Jednoróg et al., 2015; Reid, 2005; Szczerbiński, 2003), and generally in dyslexia (Bishop & Adams, 1990; Landerl et al., 1997; Peterson & Pennington, 2015; Wimmer, 1993). Previous studies have reported also a lower level of text comprehension (Ransby & Lee Swanson, 2003; Simmons & Singleton, 2000), as well as a higher number and longer duration of fixations on words in dyslexic readers (De Luca et al., 1999; Hutzler & Wimmer, 2004; Prado et al., 2007; Trauzettel-Klosinski et al., 2010).

Table 18. Summary of the results of the Experiment 4.

Variable	Group	Condition	Interaction	Mode
Reading speed	Dys < Con	C < R C < S	ns	-
Reading accuracy	Dys < Con	C < S R < S	C < S & R < S only in Dys	-
Text comprehension	Dys < Con	ns	ns	Silent < Oral
Number of fixations	Dys > Con	C < S R < S	ns	ns
Duration of fixations	Dys > Con	C > R C > S	ns	ns

Note: Dys – Dyslexic readers, Con – Typical readers;
C – condensed condition, R – regular condition, S – spaced condition

The change of inter-letter spacing had an impact on all measures of reading performance except text comprehension. Regarding reading speed, we found that sentences presented in the condensed condition (with smaller than regular spaces between the letters) were read slower than the others. However, there was no gain in reading speed in the spaced (with extra large spaces) condition as compared to the regular one. In other words, the increase of inter-letter spacing did not result in enhancement of reading speed. This finding replicates some previous reports (Dotan & Katzir, 2018; Hakvoort et al., 2017; Masulli et al., 2018; Perea et al., 2016) and stands in contrast to other studies (Duranovic et al., 2018; Sjoblom et al., 2016; Zorzi et al., 2012). The lack of increase of the reading speed may partially result from the method of measuring reading speed. In the Experiment 4 we assessed the reading speed individually for each sentence, whereas the previous studies measured the reading speed either for whole text (Sjoblom et al., 2016; Zorzi et al., 2012) or for blocks made up from several sentences (Duranovic et al., 2018; Hakvoort et al., 2017). However, the method of measurement used in the current study seems to be a more valid assessment of speed of sentence reading as it does not depend on the time between sentences in a block of text.

We found that the improvement of reading accuracy in the spaced condition as compared to both regular and condensed, was specific for the dyslexic group. Similar increases in dyslexic readers have been previously reported in the majority of studies (Dotan & Katzir, 2018; Duranovic et al., 2018; Sjoblom et al., 2016; Zorzi et al., 2012). However, one the initial research on this topic suggested that increased inter-letter spacing may enhance reading accuracy of dyslexic children to the level of typically reading peers (Zorzi et al., 2012). In the Experiment 4, the accuracy of the children with dyslexia in the spaced condition was significantly lower than the accuracy of typical readers, even in the condensed condition. In the spaced condition, dyslexic participants made over two times more errors in oral reading than typical readers did in the condensed condition. Similar phenomena have been reported in previous studies (Duranovic et al., 2018; Hakvoort et al., 2017; Sjoblom et al., 2016). Although increasing inter-letter spacing helps dyslexic children read more accurately, they are still far from the typical level of reading.

We found no impact of inter-letter spacing on the level of text comprehension. Independently of the condition, children with dyslexia understood correctly fewer sentences than their typically reading peers. Overall, the level of comprehension was high in both groups, as it differed between 84–86% in the dyslexic and 89–91% in the typically reading group (especially as compared to 46–56% and 85% in the previous study; Perea et al., 2012). The lack of effect of spacing on text comprehension replicates previous reports on typically reading adults and children (Perea et al., 2012, 2016) but differs from the a reported gain in text comprehension in dyslexic children (Perea et al., 2012). However, we applied another method of assessment of comprehension than was used in the previous studies. Instead of asking questions about the read text, we asked children to point at pictures after each sentence. This method could potentially lead to higher comprehension scores, as children had 25% of chances to guess the answer. The lack of effect of increased inter-letter spacing on comprehension sheds new light on previous, very enthusiastic reports which suggested that increased inter-letter spacing may improve reading in dyslexia (Zorzi et al., 2012). Although the dyslexic group made fewer errors reading orally in the spaced condition, the higher level of decoding was not reflected in the level of comprehension. It is possible that visual crowding affects only orthographic processing in dyslexia and has no impact on higher layers of reading, such as text comprehension. Nevertheless, we found that oral reading resulted in higher comprehension level than silent reading. This observation could be easily explained as during the oral reading children monitor their articulation and more pay more attention to the read text (Kragler, 1995).

We observed a higher number of fixations on words in the spaced than in the regular and condensed conditions. Our findings support the previous research, which reported a higher number of fixations in a spaced condition (Slattery & Rayner, 2013), though they are in contrast to another study which reported no effect of inter-letter spacing (Perea et al., 2016). The increased number of fixations in the spaced condition, although counterintuitive, may simply be a result of the length of the words (physically long because of the spaced font). We found that the bigger the inter-letter spacing, the shorter the duration of fixations. These findings are similar to the eye-tracking studies of inter-letter spacing on skilled adult readers (Perea et al., 2016; Slattery & Rayner, 2013) and both typically reading and dyslexic children (Masulli et al., 2018).

Regarding our hypotheses, we found that increased inter-letter spacing results in higher reading accuracy in the dyslexic group as well as in shorter fixation duration. These effects were either specific or more pronounced in the dyslexic group than in typical readers. The specificity of the effects for the dyslexic group may suggest that this group is particularly prone to visual crowding which, for this group, constitutes both regular and condensed texts. However, the enhancement of reading speed was observed in both typical and dyslexic readers, and found no effect of increased inter-letter spacing on the text comprehension.

Although we expected typical readers to perform significantly worse in the condensed text condition, i.e. to read slower and less accurately, no differences were observed between condensed and regular conditions in this group, in terms of all measured variables. The only visible effect in this group was a shorter fixation duration in the spaced than in the condensed condition.

Increasing inter-letter spacing does not enhance reading of a dyslexic group to a level comparable to that of typical readers, however dyslexic readers still benefit from reduced crowding to some extent, especially in case of decoding. As neither increased nor decreased inter-letter spacing has a significant impact on reading performance of typical readers, printing school books or other texts with increased inter-letter spacing would at least increase reading accuracy for dyslexic readers.

Chapter 10. General Discussion

The current thesis examined two theories of dyslexia in Polish children: the phonological deficit theory and the visual attention span theory. The current Chapter discusses the obtained results first for the phonological deficit and then for the visual attention span deficit.

Phonological deficit

Phonological skills of children with dyslexia

As expected on the basis of previous literature about phonological deficits of dyslexics in Polish (Bogdanowicz et al., 2014; Krasowicz-Kupis et al., 2009; Lipowska et al., 2008; Reid et al., 2007; Wieczorek et al., 2016) and in other transparent orthographies (Bednarek et al., 2009; Caravolas & Volín, 2001; Kortteinen et al., 2009; Morfidi et al., 2007), children with dyslexia presented limited phonological skills as compared to their typically developing peers. The differences between future dyslexics and typical readers in phonological awareness were visible already at the age of 5.5 to 8 years when participants attended first grade of a primary school or were still in the last year of kindergarten (Experiments 1b and 2). Similar early differences in phonological processing have been previously reported in other languages (Dandache et al., 2014; Torppa et al., 2010). The low level of phonological skills of the dyslexic group was persistent over time, if only phonological awareness was assessed with tasks demanding enough, such as phoneme deletion (Experiments 1a and 1b). On the other hand, if easier tasks such as phoneme analysis (Figure 11, Experiment 1b) or rhyme judgement (Table 9, Experiment 1b) were applied, the differences in scores between the typical and dyslexic readers diminished during the first two years of education. These findings both replicate previous studies which showed that in transparent languages the observed differences in phonological skills may disappear in the first years of schooling (Landerl & Wimmer, 2000;

Wimmer, 1996) if easy tasks are applied, and confirm reports that the remission of the phonological difficulties may be an artefact of the used tests (de Jong & van der Leij, 2003).

Phonological skills and reading abilities

The phonological skills were moderately to strongly related to reading abilities (Experiments 1a and 1b). The strength of the relation decreased with participants' age confirming results from other transparent languages (Landerl & Wimmer, 2000; Vaessen & Blomert, 2010; Wimmer, 1996). On the other hand, in older children the variance in phonological skills is smaller, as there are some limits of phonological abilities. In other words, if a child masters the most difficult phonological tasks (Figure 1), there is no much space for further development. Phonological awareness as measured in children who either just stared or were about to start school education was a predictor of reading skills two years later (Experiment 1b, Table 5). This finding replicates previous reports on the predictive value of early phonological skills (Bishop & Adams, 1990; Bradley & Bryant, 1983; Elbro et al., 1998; Georgiou et al., 2008; Holopainen et al., 2001; Kirby et al., 2003; MacDonald & Cornwall, 1995; Moll et al., 2016; Parrila et al., 2004; Schatschneider et al., 2004; Schneider et al., 1997; Snowling & Melby-Lervåg, 2016).

Prevalence of phonological deficit

We found that a phonological deficit (Bosse et al., 2007; Germano et al., 2014; Zoubrinetzky et al., 2014) was visible in 39–51% of Polish children with dyslexia (Experiment 1), who presented phonological skills lower than those of the 10^{th} percentile of the control group. This ratio is lower than the one found in a study on Polish adults which reported an isolated phonological deficit in 60% of sample (Reid et al., 2007), but the numbers are similar to English (Bosse et al., 2007) and French (Zoubrinetzky et al., 2014) studies which applied the same method and definition of phonological deficit (see Table 1). These very close ratios of children with dyslexia who presented low phonological skills across languages suggests that a deficit in phonological awareness is a universal symptom of reading impairment (Paulesu et al., 2001; Ziegler et al., 2003; Ziegler & Goswami, 2005) at least in alphabetic languages.

Time stability of phonological skills

The phonological abilities were stable over time, showing moderate to strong correlation between scores assessed at the beginnings of education and two years later (Experiment 1b). Even within the dyslexic group at later time, the phonological skills assessed with a one-year-long interval were moderately related (Experiment 3, Figure 19), despite more limited variance. Finally, 70% of dyslexic children who presented a phonological deficit at the first grade or in kindergarten still showed this deficit two years later. Similarly, children with a phonological deficit as assessed after two years of education already presented low phonological skills at the beginnings of schooling. These results confirm the previous findings on high stability of phonological abilities (Parrila et al., 2004; Svensson & Jacobson, 2006; Wagner et al., 1997) and the reports on reproducibility of the membership in a group with a phonological dyslexia (Peterson et al., 2014).

The unsuccessful phonological intervention

The high stability of the phonological skills has also its disadvantages which manifested in the intervention study (Experiment 3). Although previous studies consistently reported that phonological interventions are in general an effective way of improving both phonological and reading skills in children with dyslexia (Bus & van IJzendoorn, 1999; Ehri et al., 2001; Suggate, 2010), we failed to enhance the phonological or reading skills of dyslexic children with the use of phonological video games. In particular, although we observed an increase of both phonological and reading abilities of the participants of the phonological intervention, their reading improvements were at a comparable level as the increase of reading skills in a control group who did not participate in any trainings (Experiment 3, Figure 16). Perhaps, the phonological intervention used in the study was not optimal. First, the training was purely phonological, while previous meta-analyses showed that phonological trainings combined with learning of letters are particularly effective (Bus & van IJzendoorn, 1999; Ehri et al., 2001). Second, to make the phonological video game more playable, we included trainings of several abilities, whereas training one or two phonological skills may be more successful (Ehri et al., 2001). Finally, children enrolled for training were relatively old, while phonological interventions are more effective in younger children (until first grade; Suggate, 2010). Perhaps, the children had already established their strategies on solving phonological tasks (probably not optimal) and playing passive video games could not modify them.

Despite our hypothesis that the training may be of particular use in children with phonological difficulties, we found no relation between the phonological deficit and the effectiveness of the phonological intervention (Experiment 3, Figures 20 and 21). Perhaps, the comparison of children with and without a phonological deficit was invalid, as both groups had severe difficulties with phonological awareness, generally associated with dyslexia in Polish children (Krasowicz-Kupis et al., 2009; Lipowska et al., 2008), and the level of severity was not a good predictor of the possible increase of phonological skills.

Neural correlates of phonological deficit

The phonological deficit found in children with dyslexia was further supported by the results of the fMRI study (Experiment 2). Namely, we found that children with dyslexia presented a delay of development of brain structures engaged in phonological processing, such as bilateral STG, insula, left MTG, and right frontal cortex (Figure 15). These brain areas were employed by children with dyslexia during phonological processing after two years of education, when typical readers already reduced activations of these structures. Such developmental delays have been already suggested in previous literature on the neural correlates of dyslexia (Morken et al., 2017; Raschle et al., 2011)

The differences in the neural correlates of phonological processing between typical readers and children with dyslexia were visible both at the first grade or kindergarten and two years later. At the first measurement we found that children who later developed dyslexia presented a hypoactivation of left middle and inferior occipital gyri, which was consistent to previous studies on visual and orthographic processing in dyslexia (Boros et al., 2016; Cao et al., 2018; Dehaene et al., 2010). Despite this initial hypoactivation, after two years of education children with dyslexia showed higher activation of brain than typical readers. This increased activation was observed in areas which are typically associated with neural phonological network (Brennan et al., 2013) such as bilateral temporal cortices including the auditory cortex, as well as the left supramarginal and precentral and postcentral gyri, and the putamen.

Overall, we found that the phonological development of the children with dyslexia differs from the one of typical readers. Children with dyslexia not only presented lower phonological skills at all ages but also showed a delay of development of phonological neural network at the beginnings of education.

(The lack of) visual attention span deficit

The findings on the visual attention span deficit in Polish children with dyslexia stand in sharp contrast to what was found for the phonological deficit. First of all, although we expected that dyslexic children would underperform their peers in the visual attention span tasks (Bosse et al., 2007; Germano et al., 2014; Lallier et al., 2014; Yeari et al., 2017; Zoubrinetzky et al., 2014), we found the same level of visual attention span in both groups at the beginning of education and in the higher grades of primary school (Experiment 1). The studies on bilingual populations (Antzaka et al., 2018; Lallier et al., 2016) could suggest that the deficit of visual attention span should be particularly visible in in languages of transparent orthography, such as Polish. Yet, the lack of between group difference might be explained by the use of non-alphanumeric stimuli (symbols), while the deficit in visual attention span was visible mostly for alphanumeric stimuli (Banfi et al., 2018). Perhaps children with dyslexia present lower visual attention span of letters and digits as a result of limited experience with these type of stimuli due to lower exposure to print, as compared to typical readers (Castles et al., 1999; Ramus, 2001b; Stanovich et al., 1997). Second, only alphanumeric stimuli can be automatically named and it is possible that difficulties in automatic labelling of these stimuli, as a result of poor phonological representations in the dyslexic group, are responsible for group differences in visual attention span task (Ziegler et al., 2010).

Not only we found no differences in the visual attention span between typical readers and children with dyslexia, but also the level of visual attention span was not related to reading skills independently from participants' age. This results partially replicates outcomes of a cross-linguistic study, in which visual attention span skills correlated to reading abilities only in French, whereas there was no correlation in Spanish and Arabic (Awadh et al., 2016). Perhaps, visual attention span skills are more related to reading outcomes in opaque languages, as the existence of correlation was supported by other studies on French children (Bosse et al., 2007; Zoubrinetzky et al., 2014). On the other hand, the studies on bilingual populations suggested that exposure to a transparent orthography my lead to more pronounced deficits of visual attention span (Antzaka et al., 2018; Lallier et al., 2016).

Rare and unstable visual attention span deficit

A visual attention span deficit, as defined in previous studies (Bosse et al., 2007; Germano et al., 2014; Zoubrinetzky et al., 2014), was visible in 14 to 24% of children. This ratio was much lower than expected on the basis of initial research on this topic (Table 1), and only slightly higher than the percentage of typical readers who presented the same level of visual attention span skills. Previous studies consistently reported that a pure visual attention span deficit was present in about 34–44 % of children with dyslexia, and a deficit combined with an additional phonological deficit was observed in 42–72 % of children (Bosse et al., 2007; Germano et al., 2014; Zoubrinetzky et al., 2014), whereas in the current studies the ratios were two to five times lower. However, the low ratio of the children with a visual attention span deficit could simply result from the used method of assessment which was based on symbols instead of letters.

Additionally, the observed deficit of the visual attention span was not stable over time. Children who presented this deficit at one measurement showed typical visual attention span skills at the other assessment two years later (Experiment 1b). The correlation between two measurements of the visual attention span (r = .27) was also much lower than the previously reported one (r = .81; (van den Boer & de Jong, 2018)). This result is even more surprising than the low frequency of the visual attention span deficit. Namely, even if the low ratios resulted from the method of measurement, the method was exactly the same at the two testing sessions and therefore we did expect a higher stability of the scores. This suggests that the previous reports on high stability of the visual attention span of letters and digits indeed could have resulted from the experience with print which depends on familial literacy, and is quite stable over time (de Jong & Leseman, 2001; Evans et al., 2000).

Intervention based on action video games

The low stability of the visual attention span could suggest that the participants of the current study may be particularly prone to the effects of intervention: as the visual attention span of the children could spontaneously change over time, perhaps it can be trained with action video games (Antzaka et al., 2017). Again, we found a contrary result: the intervention based on AVG did not increase reading more than regular development (Experiment 3, Figure 16). Although the participants of the AVG programme improved their reading performance, the enhancement could not be linked to the intervention.

It would be interesting to check whether the improvement of reading and attentional scores in the AVG players depended on the level of visual attention span skills, especially as previous studies showed that the effects of AVG intervention are the highest in children who are able to learn playing the action games (Franceschini & Bertoni, 2019). However, we decided not to include the visual attention span factor in the analyses because of two issues discussed above: only few children presented visual attention span deficit, and it was not stable over time (Experiment 1b), therefore any conclusions on the basis of visual attention span skills measured one year earlier could be invalid .

There are several explanations why AVG intervention was not as effective as in previous studies (Franceschini et al., 2013, 2017). First of all, we - in contrast to the previous reports - included a control group who did not play any games during the time of training. Without this group we could have interpreted the gathered data as a confirmation of effectiveness of both the phonological and the attentional interventions, as we observed a gain in scores in the two groups. What is more, we included much bigger samples then those invited to previous studies, and therefore we minimized the chances for getting false positive results, which was not the case of the earlier reports (Franceschini et al., 2013, 2017).

Ad-hoc solution: increased inter-letter spacing

The only result which partially supported the visual attention span theory of dyslexia was found in the study on increased inter-letter spacing (Experiment 4). We found that indeed children with dyslexia may benefit to some extent from increased inter-letter spacing, as the spaced texts were read with fewer errors (Table 18). However, we did not observe a previously reported gain in reading speed or in the level of comprehension of the read texts (Duranovic et al., 2018;

Perea et al., 2012, 2016; Sjoblom et al., 2016; Zorzi et al., 2012). The higher accuracy of dyslexics' reading in the spaced condition may stem from the reduced visual crowding which enables dyslexic readers to identify the letters more correctly (Martelli et al., 2009; Zorzi et al., 2012). On the other hand, perhaps the increase of accuracy would be visible in both typical and dyslexic readers if only we employed more difficult stimuli which could lead to a higher error rate in typically reading children (Hakvoort et al., 2017). However, the observed gain in the reading accuracy was much lower than the one initially reported (Zorzi et al., 2012) as even in the spaced condition dyslexic readers made several times more errors than typical readers.

Conclusions

We conclude that a phonological deficit is common in Polish children with dyslexia. This deficit is not only present in about 40% of dyslexic children but also stable over time and supported by a delay in the development of the neural phonological network. Phonological skills, although severely impaired in Polish children with dyslexia, are difficult to train with computer based interventions, at least in children who already have long experience with reading. On the other hand, a visual attention span deficit is rare in Polish children with dyslexia and unstable over time. The interventions based on action video games which theoretically support visual attention are not successful in improving reading of children with dyslexia. However increase of inter-letter spaces can slightly improve the accuracy of reading in Polish children with dyslexia.

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Appendices

The Appendices include the stimuli and the R scripts used for data analysis and/or visualization in the Experiments. We included all stimuli which were not a part of standardized published psychological tests, and the scripts which can be run in the open source environment of R (R. Core Team, 2019).

The Appendices therefore include scripts used for data analyses and visualization in the Experiment 1 (Appendix 1), behavioral data visualization in the Experiment 2 (Appendix 2), data analyses and visualization in the Experiment 3 (Appendix 7) and in the Experiment 4 (Appendix 9).

The Appendices include also all stimuli which were not a part of a published tools, in particular: the stimuli used in the Rhyme and Voice tasks in the Experiment 2 (Appendix 3), a description of the phonological non-attentional video games used in the Experiment 3 (Appendix 4), the tasks used in assessment of reading and phonological skills before and after the interventions in the Experiment 3 (Appendix 5), the web-based tasks used in the intervention and control dyslexic group in the Experiment 3 (Appendix 6) and the stimuli (sentences along with their characteristics) used in the Experiment 4 (Appendix 8).

Appendix 1. The R script used in the Experiment 1

```
#EXPERIMENT 1
library(readxl)
library(psych)
library(effsize)
#Experiment 1a
Maestro <- read_excel('~/Dropbox/MŁuniewska_Doktoranckie_Nencki/DOKTORAT/Final
database_ Juventus & Maestro.xlsx', sheet = 'Maestro')
Maestro[Maestro$Status!='MLODE',]->Maestro
Maestro[!is.na(Maestro$age_TP1),]->Maestro
Maestro[complete.cases(Maestro[,c(345,358,57,58)]),]->Maestro
psych::describeBy(Maestro$Poniżej4st, Maestro$Status)
table(Maestro$Status, Maestro$Sex)
chisq.test(Maestro$Status, Maestro$Sex)
table(Maestro$Status, Maestro$Class)
chisq.test(Maestro$Status, Maestro$Class)
psych::describeBy(as.numeric(Maestro$age_TP1), Maestro$Status)
t.test(as.numeric(Maestro[Maestro$Status=='CON',]$age_TP1),as.numeric(Maestro[Maest
ro$Status=='DYS',]$age_TP1), var.equal=TRUE)
cohen.d(as.numeric(Maestro[Maestro$Status=='CON',]$age_TP1),as.numeric(Maestro[Maes
tro$Status=='DYS',]$age_TP1))

psych::describeBy(as.numeric(Maestro$SES), Maestro$Status)
t.test(as.numeric(Maestro[Maestro$Status=='CON',]$SES),as.numeric(Maestro[Maestro$S
tatus=='DYS',]$SES), var.equal=TRUE)
cohen.d(as.numeric(Maestro[Maestro$Status=='CON',]$SES),as.numeric(Maestro[Maestro$
Status=='DYS',]$SES), na.rm=TRUE)

psych::describeBy(as.numeric(Maestro$Edu_Matka_Lata), Maestro$Status)
t.test(as.numeric(Maestro[Maestro$Status=='CON',]$Edu_Matka_Lata),as.numeric(Maestr
o[Maestro$Status=='DYS',]$Edu_Matka_Lata), var.equal=TRUE)
cohen.d(as.numeric(Maestro[Maestro$Status=='CON',]$Edu_Matka_Lata),as.numeric(Maest
ro[Maestro$Status=='DYS',]$Edu_Matka_Lata), na.rm=TRUE)

psych::describeBy(as.numeric(Maestro$`KOŃCOWY: ŁĄCZNIE..351`), Maestro$Status)
t.test(as.numeric(Maestro[Maestro$Status=='CON',]$`KOŃCOWY:
ŁĄCZNIE..351`),as.numeric(Maestro[Maestro$Status=='DYS',]$`KOŃCOWY: ŁĄCZNIE..351`),
var.equal=TRUE)
cohen.d(as.numeric(Maestro[Maestro$Status=='CON',]$`KOŃCOWY:
ŁĄCZNIE..351`),as.numeric(Maestro[Maestro$Status=='DYS',]$`KOŃCOWY: ŁĄCZNIE..351`),
na.rm=TRUE)

psych::describeBy(as.numeric(Maestro$WISCR_Nonverbal_IQ), Maestro$Status)
t.test(as.numeric(Maestro[Maestro$Status=='CON',]$WISCR_Nonverbal_IQ),as.numeric(Ma
estro[Maestro$Status=='DYS',]$WISCR_Nonverbal_IQ), var.equal=TRUE)
cohen.d(as.numeric(Maestro[Maestro$Status=='CON',]$WISCR_Nonverbal_IQ),as.numeric(M
aestro[Maestro$Status=='DYS',]$WISCR_Nonverbal_IQ), na.rm=TRUE)

#PRINCIPAL COMPONENT ANALYSIS
Maestro.pca<-psych::principal(Maestro[,c(345,358,57,58)], rotate='varimax',
normalize=TRUE, nfactors=2, scores=TRUE)
summary(Maestro.pca)
print(Maestro.pca)
Maestro.pca$scores
Maestro$PCA_phono<-Maestro.pca$scores[,1]
Maestro$PCA_VA<-Maestro.pca$scores[,2]

#HIERARCHICAL REGRESSION
#RealWords
RealWords_age<-lm(Maestro$TD_slowa~as.numeric(Maestro$age_TP1))
RealWords_age_phono<-
lm(Maestro$TD_slowa~as.numeric(Maestro$age_TP1)+Maestro$PCA_phono)
RealWords_age_phono_va<-
lm(Maestro$TD_slowa~as.numeric(Maestro$age_TP1)+Maestro$PCA_phono+Maestro$PCA_VA)
RealWords_age_va<-lm(Maestro$TD_slowa~as.numeric(Maestro$age_TP1)+Maestro$PCA_VA)
```

Appendix 1. The R script used in the Experiment 1

```
RealWords_age_va_phono<-
lm(Maestro$TD_slowa~as.numeric(Maestro$age_TP1)+Maestro$PCA_VA+Maestro$PCA_phono)

anova(RealWords_age,RealWords_age_phono,RealWords_age_phono_va)
anova(RealWords_age,RealWords_age_va,RealWords_age_va_phono)

summary(RealWords_age)
summary(RealWords_age_phono)
summary(RealWords_age_phono_va)
summary(RealWords_age_va)
summary(RealWords_age_va_phono)

#Pseudowords
PseudoWords_age<-lm(Maestro$TD_pseudoslowa~as.numeric(Maestro$age_TP1))
PseudoWords_age_phono<-
lm(Maestro$TD_pseudoslowa~as.numeric(Maestro$age_TP1)+Maestro$PCA_phono)
PseudoWords_age_phono_va<-
lm(Maestro$TD_pseudoslowa~as.numeric(Maestro$age_TP1)+Maestro$PCA_phono+Maestro$PCA
_VA)
PseudoWords_age_va<-
lm(Maestro$TD_pseudoslowa~as.numeric(Maestro$age_TP1)+Maestro$PCA_VA)
PseudoWords_age_va_phono<-
lm(Maestro$TD_pseudoslowa~as.numeric(Maestro$age_TP1)+Maestro$PCA_VA+Maestro$PCA_ph
ono)

anova(PseudoWords_age,PseudoWords_age_phono,PseudoWords_age_phono_va)
anova(PseudoWords_age,PseudoWords_age_va,PseudoWords_age_va_phono)

summary(PseudoWords_age)
summary(PseudoWords_age_phono)
summary(PseudoWords_age_phono_va)
summary(PseudoWords_age_va)
summary(PseudoWords_age_va_phono)

#Identification of the children with the deficits
plot(Maestro$PCA_phono~Maestro$PCA_VA, ylab='Phonological factor', xlab='Visual
attention span factor', yliM = c(-3,3), xlim=c(-3,3), type='n')
points(Maestro[Maestro$Status=='CON',]$PCA_phono~Maestro[Maestro$Status=='CON',]$PC
A_VA, pch=1, cex=1.1)
points(Maestro[Maestro$Status=='DYS',]$PCA_phono~Maestro[Maestro$Status=='DYS',]$PC
A_VA, pch=17, cex=1.1)
abline(h=quantile(Maestro[Maestro$Status=='CON',]$PCA_phono,.10))
abline(v=quantile(Maestro[Maestro$Status=='CON',]$PCA_VA,.10))

dim(Maestro[Maestro$Status=='DYS'&Maestro$PCA_phono<quantile(Maestro[Maestro$Status
=='CON',]$PCA_phono,.10,na.rm=TRUE)&Maestro$PCA_VA>=quantile(Maestro[Maestro$Status
=='CON',]$PCA_VA,.10,na.rm=TRUE),])
dim(Maestro[Maestro$Status=='DYS'&Maestro$PCA_phono>=quantile(Maestro[Maestro$Statu
s=='CON',]$PCA_phono,.10,na.rm=TRUE)&Maestro$PCA_VA<quantile(Maestro[Maestro$Status
=='CON',]$PCA_VA,.10,na.rm=TRUE),])
dim(Maestro[Maestro$Status=='DYS'&Maestro$PCA_phono<quantile(Maestro[Maestro$Status
=='CON',]$PCA_phono,.10,na.rm=TRUE)&Maestro$PCA_VA<quantile(Maestro[Maestro$Status=
='CON',]$PCA_VA,.10,na.rm=TRUE),])
dim(Maestro[Maestro$Status=='DYS'&Maestro$PCA_phono>=quantile(Maestro[Maestro$Statu
s=='CON',]$PCA_phono,.10,na.rm=TRUE)&Maestro$PCA_VA>=quantile(Maestro[Maestro$Statu
s=='CON',]$PCA_VA,.10,na.rm=TRUE),])

psych::describeBy(as.numeric(Maestro$PCA_phono), Maestro$Status)
t.test(as.numeric(Maestro[Maestro$Status=='CON',]$PCA_phono),as.numeric(Maestro[Mae
stro$Status=='DYS',]$PCA_phono), var.equal=TRUE)
cohen.d(as.numeric(Maestro[Maestro$Status=='CON',]$PCA_phono),as.numeric(Maestro[Ma
estro$Status=='DYS',]$PCA_phono), na.rm=TRUE)

psych::describeBy(as.numeric(Maestro$PCA_VA), Maestro$Status)
t.test(as.numeric(Maestro[Maestro$Status=='CON',]$PCA_VA),as.numeric(Maestr
o$Status=='DYS',]$PCA_VA), var.equal=TRUE)
cohen.d(as.numeric(Maestro[Maestro$Status=='CON',]$PCA_VA),as.numeric(Maestro[Maest
ro$Status=='DYS',]$PCA_VA), na.rm=TRUE)
```

```
#Experiment 1b
Juv <- read_excel('~/Dropbox/MŁuniewska_Doktoranckie_Nencki/DOKTORAT/Final
database_ Juventus & Maestro.xlsx', sheet = 'Juventus')
Juv[complete.cases(Juv[,c(5,27,28,48,53,205,214,232,237)]),]->Juv
summary(Juv$`TP1_age(years)`)
sd(Juv$`TP1_age(years)`)
summary(Juv$`TP3_age(years)`)
sd(Juv$`TP3_age(years)`)

psych::describeBy(Juv$Poniżej4st, Juv$Status)

table(Juv$Status, Juv$Sex)
chisq.test(Juv$Status, Juv$Sex)
table(Juv$Status, Juv$TP1_class1or0)
chisq.test(Juv$Status, Juv$TP1_class1or0)
psych::describeBy(as.numeric(Juv$`TP1_age(years)`), Juv$Status)
t.test(as.numeric(Juv[Juv$Status=='CON',]$`TP1_age(years)`),as.numeric(Juv[Juv$Stat
us=='DYS',]$`TP1_age(years)`), var.equal=TRUE)
cohen.d(as.numeric(Juv[Juv$Status=='CON',]$`TP1_age(years)`),as.numeric(Juv[Juv$Sta
tus=='DYS',]$`TP1_age(years)`))

psych::describeBy(as.numeric(Juv$`TP3_age(years)`), Juv$Status)
t.test(as.numeric(Juv[Juv$Status=='CON',]$`TP3_age(years)`),as.numeric(Juv[Juv$Stat
us=='DYS',]$`TP3_age(years)`), var.equal=TRUE)
cohen.d(as.numeric(Juv[Juv$Status=='CON',]$`TP3_age(years)`),as.numeric(Juv[Juv$Sta
tus=='DYS',]$`TP3_age(years)`))

psych::describeBy(as.numeric(2*Juv$SES), Juv$Status)
t.test(as.numeric(2*Juv[Juv$Status=='CON',]$SES),as.numeric(2*Juv[Juv$Status=='DYS'
,]$SES), var.equal=TRUE)
cohen.d(as.numeric(2*Juv[Juv$Status=='CON',]$SES),as.numeric(2*Juv[Juv$Status=='DYS
',]$SES), na.rm=TRUE)

psych::describeBy(as.numeric(Juv$`KOŃCOWY: ŁĄCZNIE..338` ), Juv$Status)
t.test(as.numeric(Juv[Juv$Status=='CON',]$`KOŃCOWY:
ŁĄCZNIE..338`),as.numeric(Juv[Juv$Status=='DYS',]$`KOŃCOWY: ŁĄCZNIE..338`),
var.equal=TRUE)
cohen.d(as.numeric(Juv[Juv$Status=='CON',]$`KOŃCOWY:
ŁĄCZNIE..338`),as.numeric(Juv[Juv$Status=='DYS',]$`KOŃCOWY: ŁĄCZNIE..338`),
na.rm=TRUE)

psych::describeBy(as.numeric(Juv$`KOŃCOWY: ŁĄCZNIE..351`), Juv$Status)
t.test(as.numeric(Juv[Juv$Status=='CON',]$`KOŃCOWY:
ŁĄCZNIE..351`),as.numeric(Juv[Juv$Status=='DYS',]$`KOŃCOWY: ŁĄCZNIE..351`),
var.equal=TRUE)
cohen.d(as.numeric(Juv[Juv$Status=='CON',]$`KOŃCOWY:
ŁĄCZNIE..351`),as.numeric(Juv[Juv$Status=='DYS',]$`KOŃCOWY: ŁĄCZNIE..351`),
na.rm=TRUE)

psych::describeBy(as.numeric(Juv$TP2_WISCR_nonverbal_IQ), Juv$Status)
t.test(as.numeric(Juv[Juv$Status=='CON',]$TP2_WISCR_nonverbal_IQ),as.numeric(Juv[Ju
v$Status=='DYS',]$TP2_WISCR_nonverbal_IQ), var.equal=TRUE)
cohen.d(as.numeric(Juv[Juv$Status=='CON',]$TP2_WISCR_nonverbal_IQ),as.numeric(Juv[J
uv$Status=='DYS',]$TP2_WISCR_nonverbal_IQ), na.rm=TRUE)

#PRINCIPAL COMPONENT ANALYSIS TP1
JuvTP1.pca<-psych::principal(Juv[,c(27,28,48,53)], rotate='varimax',
normalize=TRUE, nfactors=2, scores=TRUE)
summary(JuvTP1.pca)
print(JuvTP1.pca)
JuvTP1.pca$scores
Juv$PCA_phono_TP1<-JuvTP1.pca$scores[,1]
Juv$PCA_VA_TP1<-JuvTP1.pca$scores[,2]

Juv$defTP1<-''
```

Appendix 1. The R script used in the Experiment 1

```
Juv[Juv$Status=='DYS'&Juv$PCA_phono_TP1<quantile(Juv[Juv$Status=='CON',]$PCA_phono_
TP1,.10,na.rm=TRUE)&Juv$PCA_VA_TP1>=quantile(Juv[Juv$Status=='CON',]$PCA_VA_TP1,.10
,na.rm=TRUE),]$defTP1='phono'
Juv[Juv$Status=='DYS'&Juv$PCA_phono_TP1>=quantile(Juv[Juv$Status=='CON',]$PCA_phono
_TP1,.10,na.rm=TRUE)&Juv$PCA_VA_TP1<quantile(Juv[Juv$Status=='CON',]$PCA_VA_TP1,.10
,na.rm=TRUE),]$defTP1='va'
Juv[Juv$Status=='DYS'&Juv$PCA_phono_TP1<quantile(Juv[Juv$Status=='CON',]$PCA_phono_
TP1,.10,na.rm=TRUE)&Juv$PCA_VA_TP1<quantile(Juv[Juv$Status=='CON',]$PCA_VA_TP1,.10,
na.rm=TRUE),]$defTP1='both'
Juv[Juv$Status=='DYS'&Juv$PCA_phono_TP1>=quantile(Juv[Juv$Status=='CON',]$PCA_phono
_TP1,.10,na.rm=TRUE)&Juv$PCA_VA_TP1>=quantile(Juv[Juv$Status=='CON',]$PCA_VA_TP1,.1
0,na.rm=TRUE),]$defTP1='none'

#HIERARCHICAL REGRESSIONS TP1
#RealWords
RealWords_TP1_age<-lm(Juv$TP1_sight_word_reading_raw
~as.numeric(Juv$`TP1_age(years)`))
RealWords_TP1_age_phono<-
lm(Juv$TP1_sight_word_reading_raw~as.numeric(Juv$`TP1_age(years)`)+Juv$PCA_phono_TP
1)
RealWords_TP1_age_phono_va<-
lm(Juv$TP1_sight_word_reading_raw~as.numeric(Juv$`TP1_age(years)`)+Juv$PCA_phono_TP
1+Juv$PCA_VA_TP1)
RealWords_TP1_age_va<-
lm(Juv$TP1_sight_word_reading_raw~as.numeric(Juv$`TP1_age(years)`)+Juv$PCA_VA_TP1)
RealWords_TP1_age_va_phono<-
lm(Juv$TP1_sight_word_reading_raw~as.numeric(Juv$`TP1_age(years)`)+Juv$PCA_VA_TP1+J
uv$PCA_phono_TP1)

anova(RealWords_TP1_age,RealWords_TP1_age_phono,RealWords_TP1_age_phono_va)
anova(RealWords_TP1_age,RealWords_TP1_age_va,RealWords_TP1_age_va_phono)

summary(RealWords_TP1_age)
summary(RealWords_TP1_age_phono)
summary(RealWords_TP1_age_phono_va)
summary(RealWords_TP1_age_va)
summary(RealWords_TP1_age_va_phono)

#Pseudowords
Pseudowords_TP1_age<-lm(Juv$TP1_pseudoword_reading_raw
~as.numeric(Juv$`TP1_age(years)`))
Pseudowords_TP1_age_phono<-
lm(Juv$TP1_pseudoword_reading_raw~as.numeric(Juv$`TP1_age(years)`)+Juv$PCA_phono_TP
1)
Pseudowords_TP1_age_phono_va<-
lm(Juv$TP1_pseudoword_reading_raw~as.numeric(Juv$`TP1_age(years)`)+Juv$PCA_phono_TP
1+Juv$PCA_VA_TP1)
Pseudowords_TP1_age_va<-
lm(Juv$TP1_pseudoword_reading_raw~as.numeric(Juv$`TP1_age(years)`)+Juv$PCA_VA_TP1)
Pseudowords_TP1_age_va_phono<-
lm(Juv$TP1_pseudoword_reading_raw~as.numeric(Juv$`TP1_age(years)`)+Juv$PCA_VA_TP1+J
uv$PCA_phono_TP1)

anova(Pseudowords_TP1_age,Pseudowords_TP1_age_phono,Pseudowords_TP1_age_phono_va)
anova(Pseudowords_TP1_age,Pseudowords_TP1_age_va,Pseudowords_TP1_age_va_phono)

summary(Pseudowords_TP1_age)
summary(Pseudowords_TP1_age_phono)
summary(Pseudowords_TP1_age_phono_va)
summary(Pseudowords_TP1_age_va)
summary(Pseudowords_TP1_age_va_phono)

#PRINCIPAL COMPONENT ANALYSIS TP3
JuvTP3.pca<-psych::principal(Juv[,c(205,214,232,237)], rotate='varimax',
normalize=TRUE, nfactors=2, scores=TRUE)
summary(JuvTP3.pca)
print(JuvTP3.pca)
JuvTP3.pca$scores
```

```
Juv$PCA_phono_TP3<-JuvTP3.pca$scores[,1]
Juv$PCA_VA_TP3<-JuvTP3.pca$scores[,2]

#HIERARCHICAL REGRESSIONS TP3
RealWords_TP3_age<-lm(Juv$TP3_sight_word_reading_raw
~as.numeric(Juv$`TP3_age(years)`))
RealWords_TP3_age_phono<-
lm(Juv$TP3_sight_word_reading_raw~as.numeric(Juv$`TP3_age(years)`)+Juv$PCA_phono_TP
3)
RealWords_TP3_age_phono_va<-
lm(Juv$TP3_sight_word_reading_raw~as.numeric(Juv$`TP3_age(years)`)+Juv$PCA_phono_TP
3+Juv$PCA_VA_TP3)
RealWords_TP3_age_va<-
lm(Juv$TP3_sight_word_reading_raw~as.numeric(Juv$`TP3_age(years)`)+Juv$PCA_VA_TP3)
RealWords_TP3_age_va_phono<-
lm(Juv$TP3_sight_word_reading_raw~as.numeric(Juv$`TP3_age(years)`)+Juv$PCA_VA_TP3+J
uv$PCA_phono_TP3)

anova(RealWords_TP3_age,RealWords_TP3_age_phono,RealWords_TP3_age_phono_va)
anova(RealWords_TP3_age,RealWords_TP3_age_va,RealWords_TP3_age_va_phono)

summary(RealWords_TP3_age)
summary(RealWords_TP3_age_phono)
summary(RealWords_TP3_age_phono_va)
summary(RealWords_TP3_age_va)
summary(RealWords_TP3_age_va_phono)

#Pseudowords
Pseudowords_TP3_age<-lm(Juv$TP3_sight_pseudoword_reading_raw
~as.numeric(Juv$`TP3_age(years)`))
Pseudowords_TP3_age_phono<-
lm(Juv$TP3_sight_pseudoword_reading_raw~as.numeric(Juv$`TP3_age(years)`)+Juv$PCA_ph
ono_TP3)
Pseudowords_TP3_age_phono_va<-
lm(Juv$TP3_sight_pseudoword_reading_raw~as.numeric(Juv$`TP3_age(years)`)+Juv$PCA_ph
ono_TP3+Juv$PCA_VA_TP3)
Pseudowords_TP3_age_va<-
lm(Juv$TP3_sight_pseudoword_reading_raw~as.numeric(Juv$`TP3_age(years)`)+Juv$PCA_VA
_TP3)
Pseudowords_TP3_age_va_phono<-
lm(Juv$TP3_sight_pseudoword_reading_raw~as.numeric(Juv$`TP3_age(years)`)+Juv$PCA_VA
_TP3+Juv$PCA_phono_TP3)

anova(Pseudowords_TP3_age,Pseudowords_TP3_age_phono,Pseudowords_TP3_age_phono_va)
anova(Pseudowords_TP3_age,Pseudowords_TP3_age_va,Pseudowords_TP3_age_va_phono)

summary(Pseudowords_TP3_age)
summary(Pseudowords_TP3_age_phono)
summary(Pseudowords_TP3_age_phono_va)
summary(Pseudowords_TP3_age_va)
summary(Pseudowords_TP3_age_va_phono)

Juv$defTP3<-''
Juv[Juv$Status=='DYS'&Juv$PCA_phono_TP3<quantile(Juv[Juv$Status=='CON',]$PCA_phono_
TP3,.10,na.rm=TRUE)&Juv$PCA_VA_TP3>=quantile(Juv[Juv$Status=='CON',]$PCA_VA_TP3,.10
,na.rm=TRUE),]$defTP3='phono'
Juv[Juv$Status=='DYS'&Juv$PCA_phono_TP3>=quantile(Juv[Juv$Status=='CON',]$PCA_phono
_TP3,.10,na.rm=TRUE)&Juv$PCA_VA_TP3<quantile(Juv[Juv$Status=='CON',]$PCA_VA_TP3,.10
,na.rm=TRUE),]$defTP3='va'
Juv[Juv$Status=='DYS'&Juv$PCA_phono_TP3<quantile(Juv[Juv$Status=='CON',]$PCA_phono_
TP3,.10,na.rm=TRUE)&Juv$PCA_VA_TP3<quantile(Juv[Juv$Status=='CON',]$PCA_VA_TP3,.10,
na.rm=TRUE),]$defTP3='both'
Juv[Juv$Status=='DYS'&Juv$PCA_phono_TP3>=quantile(Juv[Juv$Status=='CON',]$PCA_phono
_TP3,.10,na.rm=TRUE)&Juv$PCA_VA_TP3>=quantile(Juv[Juv$Status=='CON',]$PCA_VA_TP3,.1
0,na.rm=TRUE),]$defTP3='none'


#HIERARCHICAL REGRESSIONS TP13
```

Appendix 1. The R script used in the Experiment 1

```
#RealWords
RealWords_TP13_age<-lm(Juv$TP3_sight_word_reading_raw
~as.numeric(Juv$`TP1_age(years)`))
RealWords_TP13_age_phono<-
lm(Juv$TP3_sight_word_reading_raw~as.numeric(Juv$`TP1_age(years)`)+Juv$PCA_phono_TP
1)
RealWords_TP13_age_phono_va<-
lm(Juv$TP3_sight_word_reading_raw~as.numeric(Juv$`TP1_age(years)`)+Juv$PCA_phono_TP
1+Juv$PCA_VA_TP1)
RealWords_TP13_age_va<-
lm(Juv$TP3_sight_word_reading_raw~as.numeric(Juv$`TP1_age(years)`)+Juv$PCA_VA_TP1)
RealWords_TP13_age_va_phono<-
lm(Juv$TP3_sight_word_reading_raw~as.numeric(Juv$`TP1_age(years)`)+Juv$PCA_VA_TP1+J
uv$PCA_phono_TP1)

anova(RealWords_TP13_age,RealWords_TP13_age_phono,RealWords_TP13_age_phono_va)
anova(RealWords_TP13_age,RealWords_TP13_age_va,RealWords_TP13_age_va_phono)

summary(RealWords_TP13_age)
summary(RealWords_TP13_age_phono)
summary(RealWords_TP13_age_phono_va)
summary(RealWords_TP13_age_va)
summary(RealWords_TP13_age_va_phono)

#Pseudowords
Pseudowords_TP13_age<-lm(Juv$TP3_sight_pseudoword_reading_raw
~as.numeric(Juv$`TP1_age(years)`))
Pseudowords_TP13_age_phono<-
lm(Juv$TP3_sight_pseudoword_reading_raw~as.numeric(Juv$`TP1_age(years)`)+Juv$PCA_ph
ono_TP1)
Pseudowords_TP13_age_phono_va<-
lm(Juv$TP3_sight_pseudoword_reading_raw~as.numeric(Juv$`TP1_age(years)`)+Juv$PCA_ph
ono_TP1+Juv$PCA_VA_TP1)
Pseudowords_TP13_age_va<-
lm(Juv$TP3_sight_pseudoword_reading_raw~as.numeric(Juv$`TP1_age(years)`)+Juv$PCA_VA
_TP1)
Pseudowords_TP13_age_va_phono<-
lm(Juv$TP3_sight_pseudoword_reading_raw~as.numeric(Juv$`TP1_age(years)`)+Juv$PCA_VA
_TP1+Juv$PCA_phono_TP1)

anova(Pseudowords_TP13_age,Pseudowords_TP13_age_phono,Pseudowords_TP13_age_phono_va
)
summary(Pseudowords_TP13_age_phono_va)
summary(Pseudowords_TP13_age_va)
summary(Pseudowords_TP13_age_va_phono)

#PLOT TP1 and TP3

par(mfrow=c(1,2))
plot(Juv$PCA_phono_TP1~Juv$PCA_VA_TP1, ylab='Phonological factor TP1', xlab='Visual
attention span factor TP1', yliM = c(-3,3), xlim=c(-3,3), type='n')
points(Juv[Juv$Status=='CON',]$PCA_phono_TP1~Juv[Juv$Status=='CON',]$PCA_VA_TP1,
pch=1, cex=1.2)
points(Juv[Juv$Status=='DYS'&Juv$defTP3=='phono',]$PCA_phono_TP1~Juv[Juv$Status=='D
YS'&Juv$defTP3=='phono',]$PCA_VA_TP1, pch=17, cex=1.3,col='blue')
points(Juv[Juv$Status=='DYS'&Juv$defTP3=='va',]$PCA_phono_TP1~Juv[Juv$Status=='DYS'
&Juv$defTP3=='va',]$PCA_VA_TP1, pch=17, cex=1.3,col='red')
points(Juv[Juv$Status=='DYS'&Juv$defTP3=='none',]$PCA_phono_TP1~Juv[Juv$Status=='DY
S'&Juv$defTP3=='none',]$PCA_VA_TP1, pch=17, cex=1.3,col='black')
points(Juv[Juv$Status=='DYS'&Juv$defTP3=='both',]$PCA_phono_TP1~Juv[Juv$Status=='DY
S'&Juv$defTP3=='both',]$PCA_VA_TP1, pch=17, cex=1.3,col='palevioletred3')
abline(h=quantile(Juv[Juv$Status=='CON',]$PCA_phono_TP1,.10))
abline(v=quantile(Juv[Juv$Status=='CON',]$PCA_VA_TP1,.10))

plot(Juv$PCA_phono_TP3~Juv$PCA_VA_TP3, ylab='Phonological factor TP2', xlab='Visual
attention span factor TP2', yliM = c(-3,3), xlim=c(-3,3), type='n')
points(Juv[Juv$Status=='CON',]$PCA_phono_TP3~Juv[Juv$Status=='CON',]$PCA_VA_TP3,
pch=1, cex=1.2)
```

```
points(Juv[Juv$Status==‘DYS’&Juv$defTP1==‘phono’,]$PCA_phono_TP3~Juv[Juv$Status==‘D
YS’&Juv$defTP1==‘phono’,]$PCA_VA_TP3, pch=17, cex=1.3,col=‘blue’)
points(Juv[Juv$Status==‘DYS’&Juv$defTP1==‘va’,]$PCA_phono_TP3~Juv[Juv$Status==‘DYS’
&Juv$defTP1==‘va’,]$PCA_VA_TP3, pch=17, cex=1.3,col=‘red’)
points(Juv[Juv$Status==‘DYS’&Juv$defTP1==‘none’,]$PCA_phono_TP3~Juv[Juv$Status==‘DY
S’&Juv$defTP1==‘none’,]$PCA_VA_TP3, pch=17, cex=1.3,col=‘black’)
points(Juv[Juv$Status==‘DYS’&Juv$defTP1==‘both’,]$PCA_phono_TP3~Juv[Juv$Status==‘DY
S’&Juv$defTP1==‘both’,]$PCA_VA_TP3, pch=17, cex=1.3,col=‘palevioletred3’)
abline(h=quantile(Juv[Juv$Status==‘CON’,]$PCA_phono_TP3,.10))
abline(v=quantile(Juv[Juv$Status==‘CON’,]$PCA_VA_TP3,.10))

summary(as.factor(Juv$defTP1))
summary(as.factor(Juv$defTP1))/26
summary(as.factor(Juv$defTP3))
summary(as.factor(Juv$defTP3))/26
table(Juv$defTP3, Juv$defTP1)

mean(Juv[Juv$defTP1==‘phono’,]$PCA_phono_TP3)
median(Juv[Juv$defTP1==‘phono’,]$PCA_phono_TP3)
sd(Juv[Juv$defTP1==‘phono’,]$PCA_phono_TP3)
mean(Juv[Juv$defTP3==‘phono’|Juv$defTP3==‘double’,]$PCA_phono_TP1)
median(Juv[Juv$defTP3==‘phono’|Juv$defTP3==‘double’,]$PCA_phono_TP1)
sd(Juv[Juv$defTP3==‘phono’|Juv$defTP3==‘double’,]$PCA_phono_TP1)

mean(Juv[Juv$defTP1==‘va’,]$PCA_VA_TP3)
median(Juv[Juv$defTP1==‘va’,]$PCA_VA_TP3)
sd(Juv[Juv$defTP1==‘va’,]$PCA_VA_TP3)
mean(Juv[Juv$defTP3==‘va’|Juv$defTP3==‘double’,]$PCA_VA_TP1)
median(Juv[Juv$defTP3==‘va’|Juv$defTP3==‘double’,]$PCA_VA_TP1)
sd(Juv[Juv$defTP3==‘va’|Juv$defTP3==‘double’,]$PCA_VA_TP1)

psych::describeBy(as.numeric(Juv$PCA_phono_TP1 ), Juv$Status)
t.test(as.numeric(Juv[Juv$Status==‘CON’,]$PCA_phono_TP1),as.numeric(Juv[Juv$Status=
=‘DYS’,]$PCA_phono_TP1), var.equal=TRUE)
cohen.d(as.numeric(Juv[Juv$Status==‘CON’,]$PCA_phono_TP1),as.numeric(Juv[Juv$Status
==‘DYS’,]$PCA_phono_TP1), na.rm=TRUE)

psych::describeBy(as.numeric(Juv$PCA_VA_TP1 ), Juv$Status)
t.test(as.numeric(Juv[Juv$Status==‘CON’,]$PCA_VA_TP1),as.numeric(Juv[Juv$Status==‘D
YS’,]$PCA_VA_TP1), var.equal=TRUE)
cohen.d(as.numeric(Juv[Juv$Status==‘CON’,]$PCA_VA_TP1),as.numeric(Juv[Juv$Status==‘
DYS’,]$PCA_VA_TP1), na.rm=TRUE)

psych::describeBy(as.numeric(Juv$PCA_phono_TP3 ), Juv$Status)
t.test(as.numeric(Juv[Juv$Status==‘CON’,]$PCA_phono_TP3),as.numeric(Juv[Juv$Status=
=‘DYS’,]$PCA_phono_TP3), var.equal=TRUE)
cohen.d(as.numeric(Juv[Juv$Status==‘CON’,]$PCA_phono_TP3),as.numeric(Juv[Juv$Status
==‘DYS’,]$PCA_phono_TP3), na.rm=TRUE)

psych::describeBy(as.numeric(Juv$PCA_VA_TP3 ), Juv$Status)
t.test(as.numeric(Juv[Juv$Status==‘CON’,]$PCA_VA_TP3),as.numeric(Juv[Juv$Status==‘D
YS’,]$PCA_VA_TP3), var.equal=TRUE)
cohen.d(as.numeric(Juv[Juv$Status==‘CON’,]$PCA_VA_TP3),as.numeric(Juv[Juv$Status==‘
DYS’,]$PCA_VA_TP3), na.rm=TRUE)

par(mfrow=c(1,2))
plot(Juv$PCA_phono_TP1~Juv$PCA_VA_TP1, ylab=‘Phonological factor TP1’, xlab=‘Visual
attention span factor TP1’, yliM = c(-3,3), xlim=c(-3,3), type=‘n’)
points(Juv[Juv$Status==‘CON’,]$PCA_phono_TP1~Juv[Juv$Status==‘CON’,]$PCA_VA_TP1,
pch=1, cex=1.2)
points(Juv[Juv$Status==‘DYS’&Juv$defTP3==‘phono’,]$PCA_phono_TP1~Juv[Juv$Status==‘D
YS’&Juv$defTP3==‘phono’,]$PCA_VA_TP1, pch=17, cex=1.3,col=‘black’)
points(Juv[Juv$Status==‘DYS’&Juv$defTP3==‘va’,]$PCA_phono_TP1~Juv[Juv$Status==‘DYS’
&Juv$defTP3==‘va’,]$PCA_VA_TP1, pch=17, cex=1.3,col=‘black’)
points(Juv[Juv$Status==‘DYS’&Juv$defTP3==‘none’,]$PCA_phono_TP1~Juv[Juv$Status==‘DY
S’&Juv$defTP3==‘none’,]$PCA_VA_TP1, pch=17, cex=1.3,col=‘black’)
points(Juv[Juv$Status==‘DYS’&Juv$defTP3==‘both’,]$PCA_phono_TP1~Juv[Juv$Status==‘DY
S’&Juv$defTP3==‘both’,]$PCA_VA_TP1, pch=17, cex=1.3,col=‘black’)
```

```
abline(h=quantile(Juv[Juv$Status=='CON',]$PCA_phono_TP1,.10))
abline(v=quantile(Juv[Juv$Status=='CON',]$PCA_VA_TP1,.10))

plot(Juv$PCA_phono_TP3~Juv$PCA_VA_TP3, ylab='Phonological factor TP2', xlab='Visual
attention span factor TP2', yliM = c(-3,3), xlim=c(-3,3), type='n')
points(Juv[Juv$Status=='CON',]$PCA_phono_TP3~Juv[Juv$Status=='CON',]$PCA_VA_TP3,
pch=1, cex=1.2)
points(Juv[Juv$Status=='DYS'&Juv$defTP1=='phono',]$PCA_phono_TP3~Juv[Juv$Status=='D
YS'&Juv$defTP1=='phono',]$PCA_VA_TP3, pch=17, cex=1.3,col='black')
points(Juv[Juv$Status=='DYS'&Juv$defTP1=='va',]$PCA_phono_TP3~Juv[Juv$Status=='DYS'
&Juv$defTP1=='va',]$PCA_VA_TP3, pch=17, cex=1.3,col='black')
points(Juv[Juv$Status=='DYS'&Juv$defTP1=='none',]$PCA_phono_TP3~Juv[Juv$Status=='DY
S'&Juv$defTP1=='none',]$PCA_VA_TP3, pch=17, cex=1.3,col='black')
points(Juv[Juv$Status=='DYS'&Juv$defTP1=='both',]$PCA_phono_TP3~Juv[Juv$Status=='DY
S'&Juv$defTP1=='both',]$PCA_VA_TP3, pch=17, cex=1.3,col='black')
abline(h=quantile(Juv[Juv$Status=='CON',]$PCA_phono_TP3,.10))
abline(v=quantile(Juv[Juv$Status=='CON',]$PCA_VA_TP3,.10))


cor.test(Juv$PCA_VA_TP1, Juv$PCA_VA_TP3)
cor.test(Juv$PCA_phono_TP1, Juv$PCA_phono_TP3)
```

Appendix 2. The R script used in the Experiment 2

```
#wykresy
library('ggplot2',
lib.loc='/Library/Frameworks/R.framework/Versions/3.5/Resources/library')
library('Hmisc',
lib.loc='/Library/Frameworks/R.framework/Versions/3.5/Resources/library')
library('gridExCONa',
lib.loc='/Library/Frameworks/R.framework/Versions/3.5/Resources/library')
library(reaDYS)

rymy_ostateczne <- read.csv2('~/Dropbox/2018 Rhymes revision/wyniki i
obrazki/rymy_ostateczne.csv')
rymy_ostateczne[!is.na(rymy_ostateczne$RYMY_DYS),]->rymy_ostateczne
colnames(rymy_ostateczne)
cz1 <- ggplot(rymy_ostateczne, aes(x=as.factor(RYMY_DYS), y=TURA1czytprawdzsur,
fill=as.factor(RYMY_DYS))) + geom_violin() + geom_jitter(shape=16,
position=position_jitter(0.05))+labs(title='Time point 1',y='Words / min', x = '')+
scale_fill_manual(values=c('grey',
'white'))+theme_classic()+scale_x_discrete(labels=c('0' = 'CON', '1' =
'DYS'))+ylim(0,140)+theme(legend.position = 'none')
cz2 <- ggplot(rymy_ostateczne, aes(x=as.factor(RYMY_DYS), y=TURA2czytprawdzsur,
fill=as.factor(RYMY_DYS))) + geom_violin() + geom_jitter(shape=16,
position=position_jitter(0.05))+labs(title='Time point 2',y='', x = '')+
scale_fill_manual(values=c('grey',
'white'))+theme_classic()+scale_x_discrete(labels=c('0' = 'CON', '1' =
'DYS'))+ylim(0,140)+theme(legend.position = 'none')
cz3 <- ggplot(rymy_ostateczne, aes(x=as.factor(RYMY_DYS), y=TDCzytanieprawdziwe,
fill=as.factor(RYMY_DYS))) + geom_violin() + geom_jitter(shape=16,
position=position_jitter(0.05))+labs(title='Time point 3',y='', x = '')+
scale_fill_manual(values=c('grey',
'white'))+theme_classic()+scale_x_discrete(labels=c('0' = 'CON', '1' =
'DYS'))+ylim(0,140)+theme(legend.position = 'none')

af1 <- ggplot(rymy_ostateczne, aes(x=as.factor(RYMY_DYS), y=TURA1analizafonemsur,
fill=as.factor(RYMY_DYS))) + geom_violin() + geom_jitter(shape=16,
position=position_jitter(0.05))+labs(title='',y='Phoneme analysis accuracy', x =
'')+ scale_fill_manual(values=c('grey',
'white'))+theme_classic()+scale_x_discrete(labels=c('0' = 'CON', '1' =
'DYS'))+ylim(0,12)+theme(legend.position = 'none')
af2 <- ggplot(rymy_ostateczne, aes(x=as.factor(RYMY_DYS), y=TURA2analizafonemsur,
fill=as.factor(RYMY_DYS))) + geom_violin() + geom_jitter(shape=16,
position=position_jitter(0.05))+labs(title='',y='', x = '')+
scale_fill_manual(values=c('grey',
'white'))+theme_classic()+scale_x_discrete(labels=c('0' = 'CON', '1' =
'DYS'))+ylim(0,12)+theme(legend.position = 'none')
af3 <- ggplot(rymy_ostateczne, aes(x=as.factor(RYMY_DYS), y=TDphonemealysisowa,
fill=as.factor(RYMY_DYS))) + geom_violin() + geom_jitter(shape=16,
position=position_jitter(0.05))+labs(title='',y='', x = '')+
scale_fill_manual(values=c('grey',
'white'))+theme_classic()+scale_x_discrete(labels=c('0' = 'CON', '1' =
'DYS'))+ylim(0,12)+theme(legend.position = 'none')

uf1 <- ggplot(rymy_ostateczne, aes(x=as.factor(RYMY_DYS), y=TURA1usuwaniefonemsur,
fill=as.factor(RYMY_DYS))) + geom_violin() + geom_jitter(shape=16,
position=position_jitter(0.05))+labs(title='',y='Phoneme deletion accuracy', x =
'')+ scale_fill_manual(values=c('grey',
'white'))+theme_classic()+scale_x_discrete(labels=c('0' = 'CON', '1' =
'DYS'))+ylim(0,25)+theme(legend.position = 'none')
uf2 <- ggplot(rymy_ostateczne, aes(x=as.factor(RYMY_DYS), y=TURA2usuwaniefonemsur,
fill=as.factor(RYMY_DYS))) + geom_violin() + geom_jitter(shape=16,
position=position_jitter(0.05))+labs(title='',y='', x = '')+
scale_fill_manual(values=c('grey',
'white'))+theme_classic()+scale_x_discrete(labels=c('0' = 'CON', '1' =
'DYS'))+ylim(0,25)+theme(legend.position = 'none')
```

Appendix 2. The R script used in the Experiment 2

```
uf3 <- ggplot(rymy_ostateczne, aes(x=as.factor(RYMY_DYS), y=TDphonemedeletionów,
fill=as.factor(RYMY_DYS))) + geom_violin() + geom_jitter(shape=16,
position=position_jitter(0.05))+labs(title='',y='', x = '')+
scale_fill_manual(values=c('grey',
'white'))+theme_classic()+scale_x_discrete(labels=c('0' = 'CON', '1' =
'DYS'))+ylim(0,25)+theme(legend.position = 'none')

DYSCON <-grid.arrange(cz1, cz2, cz3, af1,af2,af3,uf1,uf2,uf3, ncol=3,nrow=3)
ggsave(file='DYSCON.png',DYSCON)

summary(rymy_ostateczne$TURA1wiekwlatach)
sd(rymy_ostateczne$TURA1wiekwlatach)
summary(rymy_ostateczne$wiekMRI3)
sd(rymy_ostateczne$wiekMRI3)
```

Appendix 3. Stimuli used in the fMRI task in the Experiment 2

Task	Polish words		English translation		Correct response
Rhyme	kot	płot	cat	fence	1
Rhyme	trawa	lawa	grass	lava	1
Rhyme	czapka	lody	cap	ice cream	0
Rhyme	róża	burza	rose	storm	1
Rhyme	stos	łapka	pile	paw	0
Rhyme	schody	boisko	stairs	playground	0
Rhyme	taczka	paczka	barrow	package	1
Rhyme	słoń	dłoń	elephant	hand	1
Rhyme	broda	gruszka	beard	pear	0
Rhyme	sowa	krowa	owl	cow	1
Rhyme	ptaki	woda	birds	water	0
Rhyme	czoło	koło	forehead	circle	1
Rhyme	dach	maki	roof	poppies	0
Rhyme	las	pas	forest	belt	1
Rhyme	osa	pietruszka	wasp	parsley	0
Rhyme	piach	kosa	sand	scythe	0
Rhyme	rama	brama	frame	gate	1
Rhyme	nosze	ognisko	litter	campfire	0
Rhyme	nos	kalosze	nose	rain boots	0
Rhyme	półka	bułka	shelf	bread roll	1
Voice	łapka	paczka	paw	package	1
Voice	czapka	róża	cap	rose	0
Voice	piach	stos	sand	pile	1
Voice	lawa	kot	lava	cat	1
Voice	burza	płot	storm	fence	0
Voice	nos	dach	nose	roof	0
Voice	pietruszka	las	parsley	forest	1
Voice	maki	krowa	poppies	cow	1
Voice	bułka	schody	bread roll	stairs	0
Voice	woda	sowa	water	owl	1
Voice	pas	gruszka	belt	pear	1
Voice	nosze	brama	litter	gate	0
Voice	słoń	trawa	elephant	grass	1
Voice	krowa	osa	cow	wasp	0
Voice	rama	kosa	frame	scythe	1
Voice	dłoń	ognisko	hand	campfire	0
Voice	kalosze	lody	rain boots	ice cream	0
Voice	koło	boisko	circle	playground	1
Voice	broda	taczka	beard	barrow	0
Voice	ptaki	czoło	birds	forehead	0

Appendix 4. The phonological games used as PANAVG in the Experiment 3

The description of the minigames was published in a similar form as a supplementary material along the manuscript about the effectiveness of the AVG and PNAVG interventions (Łuniewska et al., 2018).

General information

Phonological intervention was designed in a form of non-action computer game. All the games were about the life of dragons. We planned to create a game attractive for participants and thus we used colorful animations and other solutions inspired by commercial video games. For example, each correctly solved item brought coins to the player. The intervention was provided in 16 one-hour-long training sessions. The actual games were played for about 50 minutes, and at the end of the session children could spend the coins earned for the previous in-game achievements.

The intervention consisted of six basic game types. On each training session children played between two and four games of a given type, and each play lasted 2 to 4 minutes. The number and the type of games allowed in each session was predefined, but children were free to pick their order. The first training session included detailed instructions for each type of games, and during the further training sessions the instructions were shortly reminded. All games were purely auditory. The items were either words (occasionally accompanied by pictures) or pseudowords.

Chinese Dragon

Sample instruction: 'Eat items starting with /k/'.

Items: pictures paired with pictures names.

Game was similar to a popular ‘Snake’ game. The player’s task was to guide a Chinese Dragon to targets by running into them, and to avoid distractors (e.g. words starting with another phonemes).

Two-Headed Dragon

Sample instruction: ‘Type a syllable which is in the first word, and is missing in the second word’.

Items: pictures coupled with pictures names; words; pseudowords.

The player’s task was to solve the riddles asked by the Two-Headed Dragon. Each dragon’s head said one word or pseudoword, and the player’s task was to type a letter or few letters that differentiate them according to the instruction (e.g. one had said: ‘szalotka’ (shallot), and the other said: ‘szarlotka’ (apple pie); the participant was asked to type ‘R’).

It was the only game from in which a player is asked to actively produce (not click) the answer by typing it. Items selected for this game were orthographically transparent to avoid confusion caused by differences between phonology and orthography, e.g. no items in which the answer could be typed wrongly orthographically but correctly in terms of phonology were used.

Dragon Eggs

Sample instruction: ‘Choose items pairs with equal number of phonemes’.

Items: pictures paired with pictures names.

Game was similar to a popular card game known as Memory. The player’s task was to find the matching pairs by clicking and revealing the objects. The correctly matched pairs disappeared.

Dragon Babies

Sample instruction: ‘Match the dragon babies with their parents’.

Items: pseudowords

Appendix 4. The phonological games used as PANAVG in the Experiment 3

Item example: parents: /kore/, /luta/; targets: /kota/, / relu/; distractors: /kotun/, /piki/

Dragon Babies' names were a combination of their parents' names. The player's task was to match the babies and parents by dragging and dropping dragon eggs to the parents' nest.

Dragon Flirt

Sample instruction: 'Match the dragons whose names end with the same sound'

Items: pseudowords

The player's task was to match the dragons according to the rule given in the instruction.

Magician

Sample instruction: 'Select the ingredients to make the magic potion'

Items: pseudowords

The players' task was to reconstruct the formula (a pseudoword) and choose all the ingredients needed for the potion (i.e. phonemes or syllables of which the pseudoword consisted).

Items

Pseudowords were generated automatically on the basis of n-grams selected from words included in the National Corpus of Polish. First, a set of pseudowords which varied in terms of length and n-gram frequency was generated. From this set some pseudowords were selected for each game.

Difficulty levels

The items of each game differ in terms of difficulty. In particular, we manipulated item types (pictures paired with names, words, pseudowords), complexity (word frequency for words, n-gram frequency for pseudowords), and length (number of syllables and phonemes). The estimated difficulty depended also on the number of available items (e.g. a number of paris in

Dragon Eggs), as well as in the ratio of target and distractors (e.g. in Magician there could be some additional ingredients, not necessary for the formula). Finally, a crucial factor determining the difficulty level in each minigame was the exact instruction. We assumed for eample that finding rhymes is easier than matching words of the same number of phonemes or with consonants on the second position.

Adaptivity

Each type of game was included 32 to 64 minigames of growing difficulty, and each level of difficulty had three parallel versions (e.g. the same time limit but differences in eact items). The level went up if at least 75% of responses at a given level of difficulty were correct. If less than 75% of items were solved, the level was repeated, but no more than two extra times; after three failures, the game leveled up automatically.

Appendix 5. The tasks used as pretest and posttest in the Experiment 3

The description of the tasks was published in a similar form as a supplementary material along the manuscript about the effectiveness of the AVG and PNAVG interventions (Łuniewska et al., 2018).

Reading tasks

The reading tasks were adapted from the standardized battery for early detection of reading impairment, used also in the Experiment 1 (Szczerbiński & Pelc-Pękala, 2013). Children were presented with lists of words (75 items) or pseudowords (69 items) and asked to read aloud as many words as possible in 30 seconds. After 30 seconds the experimenter said: 'Stop', and repeated the procedure for the second list. Versions A and B differed in the order of the two lists. The order was List I – List II in the version A, and List II – List I in the version B.

Phoneme deletion

This task was adapted from a standardised test battery for the assessment of dyslexia (Bogdanowicz et al., 2009), used in the Experiment 1. That task of the children was to repeat an existing word with one phoneme deleted. The lists included 16 items and differed between the versions A and B. The instruction was the same as in the standardised version of the task, and was followed by three training trials with immediate feedback. There was no feedback in the test trials. The position of the target to-be-deleted consonant varied across items (word initial, word final, middle of word; single or embedded within a consonant cluster) and the two versions were matched on the basis of item difficulty as established in previous studies.

Vowel replacement

Participants' task was to repeat existing words containing vowel 'a', replacing that vowel with 'u' (version A) or 'e' (version B). The instruction for the version A was as follows: 'Let's try a secret language now. It will be called ATU because instead of the sound ‘a’ we will say ‘u’. Every time when you hear ‘a’ you will change it to ‘u’. Instead of ‘las’ you will say ‘lus’, instead of ‘ja’ you will say ‘ju’, instead of ‘mam’ - ‘mum’. What will you say instead of ‘hak’? And instead of ‘dach’? And ‘plac’? Only training trials were provided with feedback. After the eight one-syllable items, the instruction was rephrased: ‘Now try to do the same thing with the words in which there are two ‘a’ sounds. You have to replace both of them with ‘u’. Instead of ‘mama’ you will say ‘mumu’, instead of ‘tata’ - ‘tutu’, instead of ‘wata’? And instead of ‘kara’?’.

Appendix 6. The web-based reading tasks used in the Experiment 3

The description of the web-based tasks was published in a similar form as a supplementary material along the manuscript about the effectiveness of the AVG and PNAVG interventions (Łuniewska et al., 2018).

General information

Web-based reading tasks were designed in order to enable the comparisons with the control group, consisted of children who were not able to travel to the place of training and testing. The web-based tasks were completed online for four times, during leisure time at home. It took about 15 minutes to complete one testing session.

Instruction

General instructions for parents

Before each of the four sessions, parents received a remainder with the instructions on how to perform the testing session. The reminder was worded as follows:

‘We would like to remind you that it is crucial that every child completes the testing session in similar conditions. Therefore, we ask you to strictly follow the instructions below:

1. To carry out the testing session, you need a computer with an internet connection and a computer mouse. The testing should not be done on a tablet or a smartphone. Using a computer mouse enables children to give the answers quicker and makes it possible to test their reading abilities in a more reliable way.

2. We encourage you to carry out the testing when the child is relaxed, focused and willing to work.

3. The surroundings should be quiet and there should be only the child with a parent (or a caregiver) in the room.

4. All tasks have a time limit and the child will get only one attempt to complete the test.

5. Children should do the tasks without any help. They should read the short instructions before each task themselves. However, a parent (or a caregiver) may stay nearby to provide some help in case of any technical difficulties (e.g. disconnection to the internet or an accidental shutting down of the web browser) and to check whether all the tasks are completed.

6. The parent should not help the child in any other way (especially by prompting the correct answers, or indicating the incorrect answers). Only a session completed by the child himself/herself provides reliable and useful results.

7. When all tasks are finished, the completion message will be displayed. We encourage to complete all tasks at one sitting but in case of technical problems it will be possible to return to the test and finish it.

Please contact us if you have any questions or doubts.'

General instruction for children

After opening the website (linked to the child's individual account) the instruction for the child was displayed as follows: 'In a moment we will ask you to complete five short tasks. Each of them will be displayed in several parts. Try to work as fast as you can. When you click the 'Start' button, the first task will begin and you will work on your own, without any help from your parent.'

Tasks description

Each testing session consisted of five tasks, of which three was included in the analyses in the Experiment 3. The other two were a training clicking task and an orthographic sensitivity task which was not included in analysis as not assessing reading-related skills directly. Each task began with three to five training items with immediate feedback, and there was no feedback in the rest of trials. The tasks consisted of four iterations with ten items in each iteration. Every iteration finished with a massage: ‘Good job! Now try to work even faster’.

Word recognition

Each item consisted of three words. One of them was a real word in Polish (e.g. ‘własny’) and two others were pseudowords created by substituting a single letter of the target (e.g. ‘właspy’ and ‘młasny’). The task was to select the real word. The instruction was as follows: ‘You will see some real and some fake words. In each line, there will be only one real word. Click on the real words. Work as fast as you can!’. The time limit for each iteration was 20 seconds.

Sentence comprehension

The items were short sentences that were either clearly true or clearly false, e.g.: ‘Słońce świeci w dzień’ (The sun shines during the day) or ‘Bociany żywią się cukierkami’ (Storks feed on candies). The task was to assess whether the sentence is true or false. The exact instruction was: ‘You will read some sentences. Choose whether the sentence is true or false.’ The time limit for each iteration was 30 seconds.

Decoding

Each item included three pseudowords. Two of them were pseudohomophones in Polish, e.g. ‘ficka’ and ‘fidzka’, and the third, e.g. ‘fiska’, differed in pronunciation by one phoneme only. The task was to select the pseudoword of different pronunciation. The instruction was as follows: ‘Look at these words: TUK, TÓK, TUD. Two of them are pronounced the same way and one of them is pronounced differently. The word TUD is pronounced differently. The words TUK and TÓK are pronounced the same way, although they are written differently. In each line find the word that is pronounced differently than the two others.’ The time limit for each iteration was 30 seconds.

Appendix 7. The R script used for the analyses of the data in Experiment 3

```
TERAPIA_R <- read.csv2('TERAPIA_R2.csv',sep='tab')
TERAPIA_R1_dokto[1:54,]->TER
TERAPIA_R1_dokto->TERON
TER$GRUPAR[TER$Smok.czy.Krolik=='K']<-'Kroliki'
TER$GRUPAR[TER$Smok.czy.Krolik=='S']<-'Smoki'
TER$TER1.USU.INEFF <-
TER$TER1.usuwanie...czas.w.sekundach/TER$TER1.usuwanie...poprawnosc..max.16.
TER$TER2.USU.INEFF <-
TER$TER2.usuwanie...czas.w.sekundach/TER$TER2.usuwanie...poprawnosc..max.16.
TER$TER1.ZAM.INEFF <-
(TER$TER1.podmienianie.samoglosek...czas..suma./16)/(TER$TER1.podmienianie.samoglos
ek...poprawnosc..max.24./24)
TER$TER2.ZAM.INEFF <-
(TER$TER2.podmienianie.samoglosek...czas..suma./16)/(TER$TER2.podmienianie.samoglos
ek...poprawnosc..max.24./24)
TER$TER1.USU.ITEMSEC <-
TER$TER1.usuwanie...poprawnosc..max.16./TER$TER1.usuwanie...czas.w.sekundach
TER$TER2.USU.ITEMSEC <-
TER$TER2.usuwanie...poprawnosc..max.16./TER$TER2.usuwanie...czas.w.sekundach
TER$TER1.ZAM.ITEMSEC <-
TER$TER1.podmienianie.samoglosek...poprawnosc..max.24./TER$TER1.podmienianie.samogl
osek...czas..suma.
TER$TER2.ZAM.ITEMSEC <-
TER$TER2.podmienianie.samoglosek...poprawnosc..max.24./TER$TER2.podmienianie.samogl
osek...czas..suma.
TER$TER1.TSN.przedmioty.ITEMSEC <- 48/TER$TER1.TSN.przedmioty
TER$TER2.TSN.przedmioty.ITEMSEC <- 48/TER$TER2.TSN.przedmioty
TER$TER1.TSN.kolory.ITEMSEC <- 48/TER$TER1.TSN.kolory
TER$TER2.TSN.kolory.ITEMSEC <- 48/TER$TER2.TSN.kolory
TER$TER1.TSN.cyfry.ITEMSEC <- 48/TER$TER1.TSN.cyfry
TER$TER2.TSN.cyfry.ITEMSEC <- 48/TER$TER2.TSN.cyfry
TER$TER1.TSN.litery.ITEMSEC <- 48/TER$TER1.TSN.litery
TER$TER2.TSN.litery.ITEMSEC <- 48/TER$TER2.TSN.litery
TERON$TER1.USU.ITEMSEC <-
TERON$TER1.usuwanie...poprawnosc..max.16./TERON$TER1.usuwanie...czas.w.sekundach
TERON$TER2.USU.ITEMSEC <-
TERON$TER2.usuwanie...poprawnosc..max.16./TERON$TER2.usuwanie...czas.w.sekundach
TERON$TER1.ZAM.ITEMSEC <-
TERON$TER1.podmienianie.samoglosek...poprawnosc..max.24./TERON$TER1.podmienianie.sa
moglosek...czas..suma.
TERON$TER2.ZAM.ITEMSEC <-
TERON$TER2.podmienianie.samoglosek...poprawnosc..max.24./TERON$TER2.podmienianie.sa
moglosek...czas..suma.

write.csv(TER,'TER.csv')

jpeg(filenaMe = 'Figure_14.jpeg', width=1500, height =  750, units = 'px', bg =
'transparent')
par(mfrow=c(1,2), cex=1.6, family='Helvetica')
boxplot(TER[TER$GRUPAR=='Kroliki',]$TER1.czytanie.slow..suma.poprawnych,
TER[TER$GRUPAR=='Kroliki',]$TER2.czytanie.slow..suma.poprawnych,
TER[TER$GRUPAR=='Smoki',]$TER1.czytanie.slow..suma.poprawnych,
TER[TER$GRUPAR=='Smoki',]$TER2.czytanie.slow..suma.poprawnych, main = 'Word
reading', ylab='Words/minute', ylim=c(0,90),
col=c('dodgerblue4','dodgerblue3','goldenrod2','gold'), names=c('T1', 'T2', 'T1',
'T2'), family='Helvetica')
mtext('AVG', side=1, at=1.5, line=2.7, cex=2.2)
mtext('PNAVG', side=1, at=3.5, line=2.7, cex=2.2)
boxplot(TER[TER$GRUPAR=='Kroliki',]$TER1.czytanie.pseudoslow....suma.poprawnych.,
TER[TER$GRUPAR=='Kroliki',]$TER2.czytanie.pseudoslow....suma.poprawnych.,
```

```
TER[TER$GRUPAR=='Smoki',]$TER1.czytanie.pseudoslow....suma.poprawnych.,
TER[TER$GRUPAR=='Smoki',]$TER2.czytanie.pseudoslow....suma.poprawnych., main =
'Pseudoword reading', ylab='Pseduwords/minute', ylim=c(0,90),
col=c('dodgerblue4','dodgerblue3','goldenrod2','gold'), names=c('T1', 'T2', 'T1',
'T2'))
mtext('AVG', side=1, at=1.5, line=2.7, cex=2.2)
mtext('PNAVG', side=1, at=3.5, line=2.7, cex=2.2)
dev.off()

jpeg(filename = 'Figure_18_poznawcze.jpeg', width=1200, height =  1700, units =
'px', bg = 'transparent')
layout(matrix(c(1, 2, 3, 4, 5,5), nrow=3, byrow=TRUE))
par(cex=1.4)
boxplot(TER[TER$GRUPAR=='Kroliki',]$TER1.USU.ITEMSEC,
TER[TER$GRUPAR=='Kroliki',]$TER2.USU.ITEMSEC,
TER[TER$GRUPAR=='Smoki',]$TER1.USU.ITEMSEC,
TER[TER$GRUPAR=='Smoki',]$TER2.USU.ITEMSEC, main = 'Phoneme deletion',
ylab='Items/second', ylim=c(0,0.3),
col=c('dodgerblue4','dodgerblue3','goldenrod2','gold'), names=c('T1', 'T2', 'T1',
'T2'))
mtext('AVG', side=1, at=1.5, line=2.7, cex=1.8)
mtext('PNAVG', side=1, at=3.5, line=2.7, cex=1.8)
boxplot(TER[TER$GRUPAR=='Kroliki',]$TER1.ZAM.ITEMSEC,
TER[TER$GRUPAR=='Kroliki',]$TER2.ZAM.ITEMSEC,
TER[TER$GRUPAR=='Smoki',]$TER1.ZAM.ITEMSEC,
TER[TER$GRUPAR=='Smoki',]$TER2.ZAM.ITEMSEC, main = 'Vowel replacement',
ylab='Items/second', ylim=c(0,0.6),
col=c('dodgerblue4','dodgerblue3','goldenrod2','gold'), names=c('T1', 'T2', 'T1',
'T2'))
mtext('AVG', side=1, at=1.5, line=2.7, cex=1.8)
mtext('PNAVG', side=1, at=3.5, line=2.7, cex=1.8)
boxplot(TER[TER$GRUPAR=='Kroliki',]$TER1.powtarzanie.pseudoslow...poprawnosc..max27
./27,
TER[TER$GRUPAR=='Kroliki',]$TER2.powtarzanie.pseudoslow...poprawnosc..max27./27,
TER[TER$GRUPAR=='Smoki',]$TER1.powtarzanie.pseudoslow...poprawnosc..max27./27,
TER[TER$GRUPAR=='Smoki',]$TER2.powtarzanie.pseudoslow...poprawnosc..max27./27, main
= 'Pseudoword repetition', ylab='Correct responses (%)', ylim=c(0,1),
col=c('dodgerblue4','dodgerblue3','goldenrod2','gold'), names=c('T1', 'T2', 'T1',
'T2'))
mtext('AVG', side=1, at=1.5, line=2.7, cex=1.8)
mtext('PNAVG', side=1, at=3.5, line=2.7, cex=1.8)
boxplot(TER[TER$GRUPAR=='Kroliki',]$TER1KACZ/105,
TER[TER$GRUPAR=='Kroliki',]$TER2KACZ/105, TER[TER$GRUPAR=='Smoki',]$TER1KACZ/105,
TER[TER$GRUPAR=='Smoki',]$TER2KACZ/105, main = 'Selective attention', ylab='Correct
responses (%)', ylim=c(0,1),
col=c('dodgerblue4','dodgerblue3','goldenrod2','gold'), names=c('T1', 'T2', 'T1',
'T2'))
mtext('AVG', side=1, at=1.5, line=2.7, cex=1.8)
mtext('PNAVG', side=1, at=3.5, line=2.7, cex=1.8)
boxplot(TER[TER$GRUPAR=='Kroliki',]$TER1.TSN.przedmioty.ITEMSEC,
TER[TER$GRUPAR=='Kroliki',]$TER2.TSN.przedmioty.ITEMSEC,
TER[TER$GRUPAR=='Smoki',]$TER1.TSN.przedmioty.ITEMSEC,
TER[TER$GRUPAR=='Smoki',]$TER2.TSN.przedmioty.ITEMSEC,
TER[TER$GRUPAR=='Kroliki',]$TER1.TSN.kolory.ITEMSEC,
TER[TER$GRUPAR=='Kroliki',]$TER2.TSN.kolory.ITEMSEC,
TER[TER$GRUPAR=='Smoki',]$TER1.TSN.kolory.ITEMSEC,
TER[TER$GRUPAR=='Smoki',]$TER2.TSN.kolory.ITEMSEC,
TER[TER$GRUPAR=='Kroliki',]$TER1.TSN.cyfry.ITEMSEC,
TER[TER$GRUPAR=='Kroliki',]$TER2.TSN.cyfry.ITEMSEC,
TER[TER$GRUPAR=='Smoki',]$TER1.TSN.cyfry.ITEMSEC,
TER[TER$GRUPAR=='Smoki',]$TER2.TSN.cyfry.ITEMSEC,
TER[TER$GRUPAR=='Kroliki',]$TER1.TSN.litery.ITEMSEC,
TER[TER$GRUPAR=='Kroliki',]$TER2.TSN.litery.ITEMSEC,
TER[TER$GRUPAR=='Smoki',]$TER1.TSN.litery.ITEMSEC,
TER[TER$GRUPAR=='Smoki',]$TER2.TSN.litery.ITEMSEC, main = 'Rapid automatized
naming', ylab='Naming speed (items/second)', ylim=c(0,3),
col=c(rep(c('dodgerblue4','dodgerblue3','goldenrod2','gold'),4)),
names=c(rep(c('T1', 'T2', 'T1', 'T2'),4)))
```

```
abline(v=4.5, col ='grey', lwd=5, lty=2)
abline(v=8.5, col ='grey', lwd=5, lty=2)
abline(v=12.5, col ='grey', lwd=5, lty=2)
mtext('AVG', side=1, at=1.5, line=2.7, cex=1.8)
mtext('PNAVG', side=1, at=3.5, line=2.7, cex=1.8)
mtext('AVG', side=1, at=5.5, line=2.7, cex=1.8)
mtext('PNAVG', side=1, at=7.5, line=2.7, cex=1.8)
mtext('AVG', side=1, at=9.5, line=2.7, cex=1.8)
mtext('PNAVG', side=1, at=11.5, line=2.7, cex=1.8)
mtext('AVG', side=1, at=13.5, line=2.7, cex=1.8)
mtext('PNAVG', side=1, at=15.5, line=2.7, cex=1.8)
mtext('Objects', side=3, at=2.5, line=0.4, cex=2.0)
mtext('Colours', side=3, at=6.5, line=0.4, cex=2.0)
mtext('Digits', side=3, at=10.5, line=0.4, cex=2.0)
mtext('Letters', side=3, at=14.5, line=0.4, cex=2.0)
dev.off()

TERON$GRUPAR[TERON$Smok.czy.Krolik=='K']<-'Kroliki'
TERON$GRUPAR[TERON$Smok.czy.Krolik=='S']<-'Smoki'
TERON$GRUPAR[TERON$Smok.czy.Krolik=='C']<-'Kontrola'

TERON[TERON$GRUPAR=='Kroliki',]-> 'krolik'
TERON[TERON$GRUPAR=='Smoki',]-> 'smok'
TERON[TERON$GRUPAR=='Kontrola',]-> 'kontrola'

TERON[TERON$GRUPAR=='Kroliki'&TERON$FONO_deficyt==1,]-> 'krolik_def'
TERON[TERON$GRUPAR=='Kroliki'&TERON$FONO_deficyt==0,]-> 'krolik_typ'
TERON[TERON$GRUPAR=='Smoki'&TERON$FONO_deficyt==1,]-> 'smok_def'
TERON[TERON$GRUPAR=='Smoki'&TERON$FONO_deficyt==1,]-> 'smok_typ'


test_summary_FONO <-function(varnameT2, varnameT3){
  TP<-c(rep('T1',4),rep('T2',4))
  GROUP <- c(rep(c('AVG','PNAVG'),4))
  FONO <- c(rep(c('deficit','deficit','typical','typical'),2))
  M <-  as.numeric(c(mean(krolik_def[, varnameT2],na.rm=TRUE), mean(smok_def[,
varnameT2],na.rm=TRUE), mean(krolik_typ[, varnameT2],na.rm=TRUE),mean(smok_typ[,
varnameT2],na.rm=TRUE),mean(krolik_def[, varnameT3],na.rm=TRUE), mean(smok_def[,
varnameT3],na.rm=TRUE), mean(krolik_typ[, varnameT3],na.rm=TRUE),mean(smok_typ[,
varnameT3],na.rm=TRUE)))
  SD <- as.numeric(c(sd(krolik_def[, varnameT2],na.rm=TRUE), sd(smok_def[,
varnameT2],na.rm=TRUE), sd(krolik_typ[, varnameT2],na.rm=TRUE),sd(smok_typ[,
varnameT2],na.rm=TRUE),sd(krolik_def[, varnameT3],na.rm=TRUE), sd(smok_def[,
varnameT3],na.rm=TRUE), sd(krolik_typ[, varnameT3],na.rm=TRUE),sd(smok_typ[,
varnameT3],na.rm=TRUE)))
  N <- as.numeric(c(length(!is.na(krolik_def[,
varnameT2])),length(!is.na(smok_def[, varnameT2])),length(!is.na(krolik_typ[,
varnameT2])),length(!is.na(smok_typ[, varnameT2])),length(!is.na(krolik_def[,
varnameT3])),length(!is.na(smok_def[, varnameT3])),length(!is.na(krolik_typ[,
varnameT3])),length(!is.na(smok_typ[, varnameT3]))))
  SE <- SD/sqrt(N)
  CI <- 1.96*SE
  result <- data.frame(TP,GROUP,FONO,M,SD,SE,CI,N)
  return(result)}

cor.test(TER[TER$GRUPAR=='Smoki',]$PrzyrostSlow,
TER[TER$GRUPAR=='Smoki',]$TER1KACZ)
cor.test(TER$PrzyrostPseudoslow, TER$TER1KACZ)
cor.test(TER[TER$GRUPAR=='Kroliki',]$PrzyrostPseudoslow,
TER[TER$GRUPAR=='Kroliki',]$TER1KACZ)
cor.test(TER[TER$GRUPAR=='Smoki',]$PrzyrostPseudoslow,
TER[TER$GRUPAR=='Smoki',]$TER1KACZ)
dev.off()


TERLongPho <- reshape (data=TER, varying=c('TER1.USU.ITEMSEC','TER2.USU.ITEMSEC'),
v.names='phonemedel',timevar='phonemedelT', direction='long')
TERLongPho <- TERLongPho[complete.cases(TERLongPho[,c(3,4,158,159,162,163)]),]
```

Appendix 7. The R script used for the analyses of the data in Experiment 3

```
PhonemeDel.aov <- aov(phonemedel ~ (Smok.czy.Krolik*FONO_deficyt*phonemedelT)
+Error(ID/phonemedelT), data=TERLongPho)
summary(PhonemeDel.aov )

TERLongVow <- reshape (data=TER, varying=c('TER1.ZAM.ITEMSEC','TER2.ZAM.ITEMSEC'),
v.names='vowelreplace',timevar='vowelreplaceT', direction='long')
TERLongVow <- TERLongVow[complete.cases(TERLongVow[,c(3,4,158,159,162,163)]),]
TERLongVow.aov <- aov(vowelreplace ~ (Smok.czy.Krolik*FONO_deficyt*vowelreplaceT)
+Error(ID/vowelreplaceT), data=TERLongVow)
summary(TERLongVow.aov)

TERLongWord <- reshape (data=TER,
varying=c('TER1.czytanie.slow..suma.poprawnych.','TER2.czytanie.slow..suma.poprawny
ch.'), v.names='word',timevar='wordT', direction='long')
TERLongWord <- TERLongWord[complete.cases(TERLongWord[,c(3,4,18,20,35,37)]),]
TERLongWord.aov <- aov(word ~ (Smok.czy.Krolik*FONO_deficyt*wordT)
+Error(ID/wordT), data=TERLongWord)
summary(TERLongWord.aov)

TERLongPseudoWord <- reshape (data=TER,
varying=c('TER1.czytanie.pseudoslow....suma.poprawnych.','TER2.czytanie.pseudoslow.
...suma.poprawnych.'), v.names='pseudoword',timevar='pseudowordT',
direction='long')
TERLongPseudoWord <-
TERLongPseudoWord[complete.cases(TERLongPseudoWord[,c(3,4,18,20,35,37)]),]
TERLongPseudoWord.aov <- aov(pseudoword ~
(Smok.czy.Krolik*FONO_deficyt*pseudowordT) +Error(ID/pseudowordT),
data=TERLongPseudoWord)
summary(TERLongPseudoWord.aov)

TERLongPowt <- reshape (data=TER,
varying=c('TER1.powtarzanie.pseudoslow...poprawnosc..max27.','TER2.powtarzanie.pseu
doslow...poprawnosc..max27.'), v.names='powt',timevar='powtT', direction='long')
TERLongPowt <- TERLongPowt[complete.cases(TERLongPowt[,c(3,4,18,20,35,37)]),]
TERLongPowt.aov <- aov(powt ~ (Smok.czy.Krolik*FONO_deficyt*powtT)
+Error(ID/powtT), data=TERLongPowt)
summary(TERLongPowt.aov)

word_fono<-
test_summary_FONO('TER1.czytanie.slow..suma.poprawnych.','TER2.czytanie.slow..suma.
poprawnych.')
ps_fono<-
test_summary_FONO('TER1.czytanie.pseudoslow....suma.poprawnych.','TER2.czytanie.pse
udoslow....suma.poprawnych.')
usu_fono<-test_summary_FONO('TER1.USU.ITEMSEC','TER2.USU.ITEMSEC')
vow_fono<-test_summary_FONO('TER1.ZAM.ITEMSEC','TER2.ZAM.ITEMSEC')
powt_fono<-
test_summary_FONO('TER1.powtarzanie.pseudoslow...poprawnosc..max27.','TER2.powtarza
nie.pseudoslow...poprawnosc..max27.')

testow_FONO_czyt <- function(test_2, test_3){
  pd<-position_dodge(0.15)
  p2<-ggplot(test_2, aes(x=TP, y=M,
group=interaction(FONO,GROUP),color=GROUP,linetype=FONO))+
    geom_line(position=pd, size=1.8) +
    geom_point(position=pd, size=2.1) +
    geom_errorbar(aes(ymin=M-CI, ymax=M+CI), width=0.3,position=pd,
size=1.2)+expand_limits(y=0)+
    labs(title='Word reading', x = '', y = 'Items read / minute')+
    scale_linetype_manual(values=c('solid','dotted'))+
    scale_color_manual(values=c('dodgerblue3', 'goldenrod2'))+
    theme(axis.title.x=element_text(size=25),
axis.text.x=element_text(size=20),axis.title.y=element_text(size=18),
axis.text.y=element_text(size=20), legend.position='none',
title=element_text(size=20),panel.background =  element_rect(fill='gray98'))
  p3<-ggplot(test_3, aes(x=TP, y=M,
group=interaction(FONO,GROUP),color=GROUP,linetype=FONO))+
    geom_line(position=pd, size=1.8) +
```

```
    geom_point(position=pd, size=2.1) +
    geom_errorbar(aes(ymin=M-CI, ymax=M+CI), width=0.3,position=pd,
size=1.2)+expand_limits(y=0)+
    labs(title='Pseudoword reading', x = '', y = '')+
    scale_linetype_manual(values=c('solid','dotted'))+
    scale_color_manual(values=c('dodgerblue3', 'goldenrod2'))+
    theme(axis.title.x=element_text(size=25),
axis.text.x=element_text(size=20),axis.title.y=element_text(size=18),
axis.text.y=element_text(size=20), title=element_text(size=20),
legend.justification=c(1,0), legend.position=c(1,0), legend.key.size = unit(1,
'cm'), legend.text = element_text(size=18),panel.background =
element_rect(fill='gray98'))
  grid.arrange(p2, p3, ncol=2)
}

testow_FONO_czyt(word_fono,ps_fono)

testow_FONO_fono <- function(test_2, test_3, test_4){
  pd<-position_dodge(0.15)
  p2<-ggplot(test_2, aes(x=TP, y=M,
group=interaction(FONO,GROUP),color=GROUP,linetype=FONO))+
    geom_line(position=pd, size=1.8) +
    geom_point(position=pd, size=2.1) +
    geom_errorbar(aes(ymin=M-CI, ymax=M+CI), width=0.3,position=pd,
size=1.2)+expand_limits(y=0)+
    labs(title='Phoneme deletion', x = '', y = 'Items / second')+
    scale_linetype_manual(values=c('solid','dotted'))+
    scale_color_manual(values=c('dodgerblue3', 'goldenrod2'))+
    theme(axis.title.x=element_text(size=25),
axis.text.x=element_text(size=20),axis.title.y=element_text(size=18),
axis.text.y=element_text(size=20), legend.position='none',
title=element_text(size=20),panel.background =  element_rect(fill='gray98'))
  p3<-ggplot(test_3, aes(x=TP, y=M,
group=interaction(FONO,GROUP),color=GROUP,linetype=FONO))+
    geom_line(position=pd, size=1.8) +
    geom_point(position=pd, size=2.1) +
    geom_errorbar(aes(ymin=M-CI, ymax=M+CI), width=0.3,position=pd,
size=1.2)+expand_limits(y=0)+
    labs(title='Vowel replacement', x = '', y = 'Items / second')+
    scale_linetype_manual(values=c('solid','dotted'))+
    scale_color_manual(values=c('dodgerblue3', 'goldenrod2'))+
    theme(axis.title.x=element_text(size=25),
axis.text.x=element_text(size=20),axis.title.y=element_text(size=18),
axis.text.y=element_text(size=20), legend.position='none',
title=element_text(size=20),panel.background =  element_rect(fill='gray98'))
  p4<-ggplot(test_4, aes(x=TP, y=M,
group=interaction(FONO,GROUP),color=GROUP,linetype=FONO))+
    geom_line(position=pd, size=1.8) +
    geom_point(position=pd, size=2.1) +
    geom_errorbar(aes(ymin=M-CI, ymax=M+CI), width=0.3,position=pd,
size=1.2)+expand_limits(y=0)+
    labs(title='Pseudoword repetition', x = '', y = 'Correct responses')+
    scale_linetype_manual(values=c('solid','dotted'))+
    scale_color_manual(values=c('dodgerblue3', 'goldenrod2'))+
    theme(axis.title.x=element_text(size=25),
axis.text.x=element_text(size=20),axis.title.y=element_text(size=18),
axis.text.y=element_text(size=20), title=element_text(size=20),
legend.justification=c(1,0), legend.position=c(1,0), legend.key.size = unit(1,
'cm'), legend.text = element_text(size=18),panel.background =
element_rect(fill='gray98'))
  grid.arrange(p2, p3, p4, ncol=3)
}

testow_FONO_fono(usu_fono, vow_fono, powt_fono)

cor(TER$FONO, TER$TER1.usuwanie...poprawnosc..max.16, use='pairwise')
cor(TER$FONO, TER$TER1.USU.ITEMSEC, use='pairwise')
cor(TER$FONO, TER$TER1.ZAM.ITEMSEC, use='pairwise')
```

Appendix 7. The R script used for the analyses of the data in Experiment 3

```
cor(TER$FONO, TER$TER1.podmienianie.samoglosek...poprawnosc..max.24.,
use='pairwise')


par(mfrow=c(1,3))
plot(TER$TER1.USU.ITEMSEC~TER$FONO,main='Phoneme deletion',xlab='Phonological
factor (Experiment 1a)', ylab='Items / second', type='n',ylim=c(0,0.25),)
points(TER[TER$FONO_deficyt==1,]$TER1.USU.ITEMSEC~TER[TER$FONO_deficyt==1,]$FONO,
pch =1, cex = 1.2, col = 'dodgerblue')
points(TER[TER$FONO_deficyt==0,]$TER1.USU.ITEMSEC~TER[TER$FONO_deficyt==0,]$FONO,
pch =19, cex = 1.2, col = 'dodgerblue')

plot(TER$TER1.ZAM.ITEMSEC~TER$FONO,main='Vowel replacement',xlab='Phonological
factor (Experiment 1a)', ylab='Items / second', type='n',ylim=c(0,0.6),)
points(TER[TER$FONO_deficyt==1,]$TER1.ZAM.ITEMSEC~TER[TER$FONO_deficyt==1,]$FONO,
pch =1, cex = 1.2, col = 'dodgerblue')
points(TER[TER$FONO_deficyt==0,]$TER1.ZAM.ITEMSEC~TER[TER$FONO_deficyt==0,]$FONO,
pch =19, cex = 1.2, col = 'dodgerblue')

plot(TER$TER1.powtarzanie.pseudoslow...poprawnosc..max27./27~TER$FONO,main='Pseudow
ord repetition',xlab='Phonological factor (Experiment 1a)', ylab='Correct responses
(%)', type='n',ylim=c(0,1),)
points(TER[TER$FONO_deficyt==1,]$TER1.powtarzanie.pseudoslow...poprawnosc..max27./2
7~TER[TER$FONO_deficyt==1,]$FONO, pch =1, cex = 1.2, col = 'dodgerblue')
points(TER[TER$FONO_deficyt==0,]$TER1.powtarzanie.pseudoslow...poprawnosc..max27./2
7~TER[TER$FONO_deficyt==0,]$FONO, pch =19, cex = 1.2, col = 'dodgerblue')

t.test(TER$TER1.powtarzanie.pseudoslow...poprawnosc..max27.~TER$FONO_deficyt)

sd(TER[TER$FONO_deficyt==1,]$TER1.powtarzanie.pseudoslow...poprawnosc..max27.,
na.rm=TRUE)
sd(TER[TER$FONO_deficyt==0,]$TER1.powtarzanie.pseudoslow...poprawnosc..max27.,
na.rm=TRUE)
```

Appendix 8. Stimuli used in the Experiment 4

LW – length in words
LL – length in letters
DL – difficulty level
LS – length in syllables
CO – condition in set A (C – condensed, N – regular, S – spaced)

Sentence	**LW**	**LL**	**DL**	**LS**	**CO**
Oni wspólnie przelewają mleko.	4	27	1	9	C
Ktoś niedbale wcisnął pobrudzoną białą łyżkę pod gazetę.	8	49	4	18	N
Ona mu nie macha.	4	14	1	5	S
On oddaje jej zabawkę.	4	19	1	8	S
Dzieci, stojąc naprzeciwko siebie, jedzą z apetytem soczyste owoce i uśmiechają się.	12	73	3	26	N
Szklanka stoi pod kwadratowym stołem.	5	33	4	11	N
Oni plotkują, siedząc na ławce.	5	27	2	9	C
Podskakującego z radości mężczyznę pokazuje kilkulatek.	6	50	7	21	N
On siedzi, a ona stoi.	5	18	1	6	C
Obdarowywana osoba ma buty na obcasie.	6	33	6	15	N
Klocki sprzątane przez chłopca są rozsypane po całej podłodze.	9	54	4	19	C
Krótkowłosa dziewczynka w zielonym sweterku pokazuje palcem biegnącą panią.	9	67	7	25	S
Stół, na którym wyleguje się szary prześliczny kotek, jest niebieściutki.	10	64	5	21	N
Przed stojącym w korku ambulansem czeka śmieciarka.	7	45	3	16	C
Nowoczesna lampa przemysłowa zawieszona nisko nad stołem znacząco odbiega od niego pod względem koloru.	14	90	5	34	S
Chłopiec noszący niebieskie dżinsy samodzielnie sprząta rozsypane klocki.	8	66	7	23	N
Młodsza siostrzyczka pokazuje bratu prześliczne delikatne zwierzątko.	7	63	7	21	C
Dwa urocze misie posadzono blisko i skierowano do siebie nawzajem miękkimi, pluszowymi pleckami.	13	84	1	32	S
Zwierzę wyprowadzane przez panią na spacer jest tak gigantyczne, że może na nim siedzieć dziecko.	15	83	3	28	S
Dziewczynka przytrzymuje niesforne psisko, które głaszcze chłopiec.	7	61	5	18	N
Popijając wodę, chłopiec wita się ze swoim nauczycielem.	8	49	3	18	C
Dziewczynka w białych podkolanówkach wręcza swojemu koledze książkę wartą przeczytania.	10	78	5	27	N
Pełen entuzjazmu mąż pokazuje żonie samolot, o którego posiadaniu marzył od dzieciństwa.	12	77	5	30	C
Na stole stoi plastikowa butelka z żółtym płynem przypominającym nieco olej.	11	66	6	25	S
Cierpliwie czekające w kolejce dzieci są niemal identycznego wzrostu.	9	61	5	22	S
Do dziewczynki, która siedzi spokojnie na ławce i je bułkę, macha pani jedząca lody.	14	71	3	27	C
Biały kwiatek o sześciu płatkach rewelacyjnie prezentuje się w niebieskim wazonie.	11	72	5	26	N
Wysportowana dziewczynka beztrosko mknie na deskorolce.	6	50	6	17	N
Pasjonująca książka trafiła w ręce zafascynowanego nią okularnika.	8	59	7	25	N
Nikt nie karmi ptaszka pokazywanego przez dziewczynkę.	7	48	5	16	S
Przed wesołym pieskiem ucieka osoba mająca czerwony beret i zielone kalosze.	11	66	4	25	C

Appendix 8. Stimuli used in the Experiment 4

Sentence	LW	LL	DL	LS	CO
Zielona łyżeczka leży w miseczce, która nie jest biała.	9	47	1	18	N
Na zielonkawym okrągłym stole stoi pusta szklana butelka.	8	50	4	17	N
Grzebień, na którym leży lusterko, jest długi, ale nie jest czerwony.	11	59	1	19	C
Dziewczyna, która stoi za niskim murkiem z rudej cegły, ma rozpuszczone włosy.	12	67	3	23	S
Żadna z dziewczynek stojących obok huśtawki nie wplotła we włosy wstążki.	11	63	3	21	S
W korku tuż przed czerwonym autobusem stoi karetka pogotowia.	9	53	4	20	N
Chłopiec wygląda zza ogrodzenia prawie tak wysokiego, jak on sam.	10	56	2	20	S
Ciemnowłosy chłopiec zwraca uwagę na wolno drepczącego żółwia.	8	55	5	19	S
Chłopcy w pstrokatych czapeczkach stoją przed zadumaną dziewczynką noszącą fioletową sukienkę.	11	84	6	30	S
Pan noszący czapkę jest bardzo zadowolony, chociaż nie wziął dzisiaj z mieszkania aktówki.	13	78	3	27	S
Uśmiechnięta blondynka trzyma ogromny widelec i dopiero zabiera się do jedzenia.	11	70	2	25	N
Za panią pchającą taczkę wypełnioną po brzegi liśćmi biegnie uradowany chłopaczek.	11	72	5	27	C
Zielonkawa drewniana ławka, na której siedzi dziewczynka w żółtych spodenkach, jest szeroka.	12	81	3	26	N
Nastolatek niepotrzebujący śliniaka zajada się torcikiem z wisienką.	8	61	7	24	S
Czyjaś bluza, choć pozbawiona kaptura, ma zupełnie sprawny suwak.	9	57	4	20	N
Pan w zielonej bluzie, podskakując z niepohamowanej radości, biegnie w lewą stronę.	12	72	6	28	N
Chłopiec w czerwonych spodenkach i koszulce z białym numerem jeden odbija czerwoną piłkę.	13	77	3	29	C
Biała łyżeczka nie leży na gazecie, tylko pod książką.	9	46	1	17	C
Zwierzątko pokazywane przez chłopca przycupnęło pod niewielkim drzewem.	8	64	6	21	S
Pan boleśnie gryziony przez zadziorną kozę ma spodnie w tym samym kolorze, co czapkę.	14	72	4	25	N
Pani trzymająca błękitną teczkę uśmiecha się przyjaźnie do nieśmiałego chłopca.	10	70	5	24	N
Z dwóch wspólnie spędzających popołudnie osób tylko jedna siedzi na ławce.	11	64	4	22	S
Pojazd, za pomocą którego przemieszcza się chłopiec, jest niewielki i czerwony.	11	69	3	23	S
Podczas długiej przerwy dzieci jedzące drugie śniadanie witają się ze sobą.	11	65	4	23	N
Delikatny przedmiot postawiony pod stołem ma wąską szyjkę i jest wykonany z hartowanego szkła.	14	81	5	31	S
Na parkowej ławce, na której odpoczywa chłopiec, leży książka.	9	54	3	19	S
Osobą uciekającą w popłochu przed rozpędzonym słoniem jest dziewczynka w czapeczce.	11	73	4	25	N
Ktoś umieścił białe wiaderko w niebieskim kartonie z gwiazdkami, żeby poprawić wystrój mieszkania.	13	86	3	29	C
Dziewczynka w kucykach stoi za wysokim murkiem.	7	41	2	14	C
W dość krótkiej kolejce chłopiec czeka za dziewczynkami.	8	49	2	16	C
Stolik jest tak niski, że trudno byłoby wcisnąć pod niego stojące na nim naczynie.	14	69	1	24	N
Pan z plecakiem stoi naprzeciwko dziewczynki w warkoczykach.	8	53	3	18	C
Dziewczynka stojąca przed chłopcami, którzy noszą różnobarwne czapeczki, ma długie warkocze.	11	82	4	27	S
Biały kwiatek stoi w kanarkowym flakonie.	6	36	4	13	S
Choć goniące dziewczynkę zwierzę jest malutkie, ona i tak panicznie się go boi.	13	67	2	22	S
Nonszalancko opierający się o płot nastolatek ma sweter w kolorze jajecznicy.	11	67	6	26	C

Sentence	LW	LL	DL	LS	CO
Przystojny pan został obdarowany przez swoją adoratorkę okazałym prezentem.	9	67	7	25	C
Mężczyzna w kapeluszu o przestarzałym kroju przechadza się dostojnym krokiem przed krową.	12	78	4	27	C
Uradowana dziewczynka musi podskoczyć, żeby złapać lecącą w jej kierunku zieloną piłkę.	12	76	3	29	N
Dziewczynka ani nie siedzi, ani nie je.	7	33	1	10	N
Na dębowym stole stoi żółto-zielona lampka w kwiatki, którą zapomniano podłączyć do kontaktu.	13	81	1	28	C
Chłopiec siedzi, ale nie je.	5	24	1	8	S
Chłopiec, któremu dziewczynka daje pić, ma pomarańczowy sweter.	8	56	3	20	S
Mama rozczesuje długie włosy córeczki żółtą szczotką.	7	47	5	17	N
Laurką, jaką otrzymała mama od kilkuletniego synka, był realistyczny rysunek ich wspólnego domu.	13	84	5	31	C
Zabawki witających się ze sobą dzieci wzbijają się w powietrze ponad nimi.	12	63	2	25	C
Za kroczącym rumakiem podąża jego nosząca kapelusz właścicielka.	8	57	6	22	C
Gliniane naczynie postawione na stole ma spore ucho.	8	45	4	17	S
Wszyscy chłopcy stojący przed dziewczynką mają wielobarwne czapki z daszkiem.	10	68	5	22	S
Pan w zielonym swetrze i stylowym białym kaszkiecie trzyma pod pachą pękatą teczkę z dokumentami.	15	83	3	32	N
Dziewczynki, które rozglądają się, stojąc obok chłopca w zielonej koszulce, wpięły kokardki we włosy.	14	88	3	30	S
Niewyszukany stół, pod którym stoi kolorowa lampa, jest kwadratowy i beżowy.	11	66	6	25	N
Pies, przed którym zwinnie ucieka przerażony chłopiec, jest niegroźny, choć wyjątkowo masywny.	12	83	4	26	C
Lusterko, na którym położono króciutki grzebień, jest okrągłe, ale nie jest zielone.	12	73	1	24	C
Dziewczynka trzymająca balonik spotyka chłopca puszczającego latawiec.	7	64	6	23	S
Zmęczony długotrwałymi psotami kocur odpoczywa tuż obok swojej właścicielki.	9	68	7	25	C
Osoba wracająca z zakupów niesie niepozorny koszyczek pełen świeżutkich, chrupiących bagietek.	11	84	7	30	N
Radosna właścicielka króliczka wita się z panią wyprowadzającą na spacer rasowego jamnika.	12	79	6	32	C
Konewka używana do podlewania kwiatów rosnących w okrągłej doniczce jest pomarańczowa.	11	76	6	28	C

Appendix 9. The R script used for the analyses in the Experiment 4

```
library(readxl)
library(ggplot2)
library(emmeans)
library(ez)
library(Hmisc)

url <- 'https://osf.io/wg4q9/download'
destfile <- 'download.xlsx'
curl::curl_download(url, destfile)
download <- read_excel(destfile)
data<-download

data$Group[data$Group=='CON']<-'Typical readers'
data$Group[data$Group=='DYS']<-'Dyslexic readers'
data$FixationDuration<-data$FixationDuration*1000
dataAloud<-data[data$Mode=='Aloud',]
data[data$FixNOUT==0,]->dataFixN
data[data$FixOUT==0,]->dataFix


#Reading Speed
aggregate(ReadingSpeed~Group+Condition,data=data,mean,na.rm=TRUE)
aggregate(ReadingSpeed~Group+Condition,data=data,sd,na.rm=TRUE)
ReadingSpeed.aov <- aov(ReadingSpeed ~ (Group*Condition)
+Error(ParticipantID/(Condition)), data=data)
print(summary(ReadingSpeed.aov))
ReadingSpeed.emm.main<- emmeans(ReadingSpeed.aov, ~ Condition)
pairs(ReadingSpeed.emm.main)
ReadingSpeed.ez<- ezANOVA(data=dataAloud, dv=ReadingSpeed, wid=ParticipantID,
within=Condition,between=Group)
ReadingSpeed.ez$ANOVA[,c(1,7)]

p <- qplot(as.factor(Condition),ReadingSpeed,data=data,geom='violin',color=Group,
fill=Group)
p <- p+labs(x='Condition',y='Average reading speed (words/min)')
p <- p+ stat_summary(fun.y = mean, geoM = 'line', aes(group =
Group),position=position_dodge(width=.75))
p <- p + stat_summary(fun.data = mean_cl_boot, geom='pointrange', color='white',
position=position_dodge(width=.90),size=.35)
p <- p + scale_x_discrete(labels=c('Condensed', 'Regular', 'Spaced'))
p <- p + theme(panel.background = element_rect(fill = 'transparent', colour = NA))
p <- p + theme(panel.grid.major = element_line(colour='grey', size=0.2))
ggsave('Words_per_minute.jpg',plot=p,width=6, height=4, dpi=600)


#Reading Accuracy - number of errors
aggregate(Errors_oral~Group+Condition,data=data,mean,na.rm=TRUE)
aggregate(Errors_oral~Group+Condition,data=data,sd,na.rm=TRUE)
Err.aov <- aov(Errors_oral ~ (Group*Condition) +Error(ParticipantID/(Condition)),
data=data)
print(summary(Err.aov))
Err.emm.main<- emmeans(Err.aov, ~ Condition)
pairs(Err.emm.main)
Err.emm<- emmeans(Err.aov, ~ Condition*Group)
pairs(Err.emm)
Err.ez<- ezANOVA(data=dataAloud, dv=Errors_oral, wid=ParticipantID,
within=Condition,between=Group)
Err.ez$ANOVA[,c(1,7)]

p <- qplot(as.factor(Condition),Errors_oral,data=data,geom='violin',color=Group,
fill=Group)
p <- p+labs(x='Condition',y='Average number of errors')
p <- p+ stat_summary(fun.y = mean, geoM = 'line', aes(group =
Group),position=position_dodge(width=.75))
```

```
p <- p + stat_summary(fun.data = mean_cl_boot, geom='pointrange', color='white',
position=position_dodge(width=.90),size=.35)
p <- p + scale_x_discrete(labels=c('Condensed', 'Regular', 'Spaced'))
p <- p + theme(panel.background = element_rect(fill = 'transparent', colour = NA))
p <- p + theme(panel.grid.major = element_line(colour='grey', size=0.2))
ggsave('Err.jpg',plot=p,width=6, height=4, dpi=600)

#Comprehension
aggregate(Comprehension~Group+Condition+Mode,data=data,mean,na.rm=TRUE)
aggregate(Comprehension~Group+Condition+Mode,data=data,sd,na.rm=TRUE)
Comprehension.aov <- aov(Comprehension ~ (Group*Condition*Mode)
+Error(ParticipantID/(Condition*Mode)), data=data)
print(summary(Comprehension.aov))
Comprehension.emm<- emmeans(Comprehension.aov, ~ Condition*Group*Mode)
pairs(Comprehension.emm)
Comprehension.emm.mode<- emmeans(Comprehension.aov, ~ Mode)
pairs(Comprehension.emm.mode)
Comprehension.ez<- ezANOVA(data=data, dv=Comprehension, wid=ParticipantID,
within=.(Condition,Mode),between=Group)
Comprehension.ez$ANOVA[,c(1,7)]

p <- qplot(as.factor(Condition),Comprehension,data=data,geom='violin',color=Group,
fill=Group)
p <- p+labs(x='Condition',y='Comprehension accuracy')
p <- p+ stat_summary(fun.y = mean, geoM = 'line', aes(group =
Group),position=position_dodge(width=.75))
p <- p + stat_summary(fun.data = mean_cl_boot, geom='pointrange', color='white',
position=position_dodge(width=.90),size=.35)
p <- p + scale_x_discrete(labels=c('Condensed', 'Regular', 'Spaced'))
p <- p + theme(panel.background = element_rect(fill = 'transparent', colour = NA))
p <- p + theme(panel.grid.major = element_line(colour='grey', size=0.2))
ggsave('Comprehension.jpg',plot=p,width=6, height=4, dpi=600)


#Number of fixations
aggregate(FixationNumber~Group+Condition+Mode,data=dataFixN,mean,na.rm=TRUE)
aggregate(FixationNumber~Group+Condition+Mode,data=dataFixN,sd,na.rm=TRUE)
FixN.aov <- aov(FixationNumber ~ (Group*Condition*Mode)
+Error(ParticipantID/(Condition*Mode)), data=dataFixN)
print(summary(FixN.aov))
FixN.emm.main<- emmeans(FixN.aov, ~ Condition)
pairs(FixN.emm.main)
FixN.ez<- ezANOVA(data=dataFixN, dv=FixationNumber, wid=ParticipantID,
within=.(Condition,Mode),between=Group)

p <-
qplot(as.factor(Condition),FixationNumber,data=dataFixN,geom='violin',color=Group,
fill=Group)
p <- p+labs(x='Condition',y='Average number of fixations on a word')
p <- p+ stat_summary(fun.y = mean, geoM = 'line', aes(group =
Group),position=position_dodge(width=.75))
p <- p + stat_summary(fun.data = mean_cl_boot, geom='pointrange', color='white',
position=position_dodge(width=.90),size=.35)
p <- p + scale_x_discrete(labels=c('Condensed', 'Regular', 'Spaced'))
p <- p + theme(panel.background = element_rect(fill = 'transparent', colour = NA))
p <- p + theme(panel.grid.major = element_line(colour='grey', size=0.2))
ggsave('FixN.jpg',plot=p,width=6, height=4, dpi=600)


#Duration of fixations
aggregate(FixationDuration~Group+Condition+Mode,data=dataFix,mean,na.rm=TRUE)
aggregate(FixationDuration~Group+Condition+Mode,data=dataFix,sd,na.rm=TRUE)
FixationDuration.aov <- aov(FixationDuration ~ (Group*Condition*Mode)
+Error(ParticipantID/(Condition*Mode)), data=dataFix)
print(summary(FixationDuration.aov))
FixationDuration.emm.main<- emmeans(FixationDuration.aov, ~ Condition)
pairs(FixationDuration.emm.main)
```

Appendix 9. The R script used for the analyses in the Experiment 4

```
FixationDuration.ez<- ezANOVA(data=dataFix, dv=FixationDuration, wid=ParticipantID,
within=.(Condition,Mode),between=Group)

p <-
qplot(as.factor(Condition),FixationDuration,data=dataFix,geom='violin',color=Group,
fill=Group)
p <- p+labs(x='Condition',y='Average fixation duration (ms)')
p <- p+ stat_summary(fun.y = mean, geoM = 'line', aes(group =
Group),position=position_dodge(width=.75))
p <- p + stat_summary(fun.data = mean_cl_boot, geom='pointrange', color='white',
position=position_dodge(width=.90),size=.35)
p <- p + scale_x_discrete(labels=c('Condensed', 'Regular', 'Spaced'))
p <- p + theme(panel.background = element_rect(fill = 'transparent', colour = NA))
p <- p + theme(panel.grid.major = element_line(colour='grey', size=0.2))
ggsave('Fix.jpg',plot=p,width=6, height=4, dpi=600)
```