Multi-Character Processing Intervention in an English-Speaking Child with Dyslexia

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Summary

The aims of this study were to determine (1) whether multi-character processing can be trained; and if so, (2) can it lead to improvements in reading and (3) other cognitive skills. We further aimed to investigate (4) whether training of multi-character processing improves visual attention span.

We report a single case intervention study with an English-speaking girl with dyslexia, YR (8 years, 10 months), who also had a deficit in multi-character processing. We administered various cognitive skills measures (e.g. reading skills, visual working memory capacity, visual short-term memory capacity, rapid automatized naming, visual attention span) twice before and once after the intervention in order to clarify the relationship between multi-character processing and reading and to uncover cognitive mechanisms causally related to a deficit in multi-character processing. We compared YR's results to seven age-matched typical readers (mean age 8 years, 9 months). YR's multi-character processing skills improved significantly after the intervention, but there was no improvement observed in her reading skills. The findings are discussed within theoretical reading models.

Statement of Originality

I, Iuliia Fokina, certify that this thesis titled "Multi-character processing intervention in an English-speaking child with dyslexia" is an original piece of research that has been written by me and is entirely my own work except where I have given full documented references to the work of others. All the help and assistance that I have received in the preparation of this thesis has been properly acknowledged. The materials of this thesis have not previously been submitted for a higher degree or as part of requirements for a degree to any university or institution. In addition, I certify that all information sources and literature used are indicated in the thesis. This project was approved by the Macquarie University Human Ethics Committee (Ref: 5201300197).

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Introduction

Reading and developmental dyslexia

Reading is a complex cognitive skill that is normally distributed within the population (Shaywitz, Escobar, Shaywitz, Fletcher, & Makuch, 1992). Therefore, the reading abilities of around 16% of children fall below the average range for their age or grade, and 5% of children have significant difficulties with reading (McArthur & Castles, 2017). These children are often said to have "poor reading" or "developmental dyslexia" or "reading impairment" or "reading disability". In this dissertation, we will simply use the term dyslexia.

The importance of reading in modern society is enormous – we can hardly imagine doing anything or going anywhere nowadays without reading written instructions. Tasks such as reading a book or doing homework can be extremely challenging for a child with dyslexia, which puts them at risk for low self-esteem, anxiety, depression and even attempted suicide (for a summary, see McArthur & Castles, 2017). It is therefore important to provide effective intervention programs for those who experience dyslexia.

Heterogeneity of dyslexia

Not all children with dyslexia have the same types of reading problems. The heterogeneity of dyslexia has been captured in different theoretical models (e.g., Marshall, 1984; Wolf & Bowers, 1999). Here, we focus on dual route theory to describe the heterogeneous presentation of dyslexia. For example, some can easily learn the letter-sounds rules of a language, allowing them to correctly read words that follow the letter-sound rules (regular words) but struggle to learn to read words that do not follow these rules (irregular words). This pattern of reading has been referred to surface dyslexia (e.g., Friedmann & Lukov, 2008; Jones, Castles, & Kohnen, 2011). Other children show the reverse pattern: they can easily learn to read irregular words but they have trouble with reading new words or nonwords which can be read correctly by applying letter-sound rules (phonological dyslexia; (e.g., Coltheart, 1996; Larsen, Kohnen, McArthur, & Nickels, 2018)). Many children have problems with learning to read both unfamiliar and irregular words, which has been called mixed dyslexia (e.g., Friedmann & Coltheart, n.d.; McArthur et al., 2013).

One model that has been used to decribe different reading impairments such as these is the dual route model (Figure 1) (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). This model suggests that there are two information processing routes. In the nonlexical route, letters are translated into sounds (via grapheme-phoneme correspondence rules) that are used to pronounce words aloud. This route produces correct pronunciations for regular words (e.g., marsh) and unfamiliar words or made up words (nonwords, e.g., phleptish). In the lexical route, orthographic and phonological lexicons are used to translate whole words into their spoken representations. This route produces correct pronunciations for familiar regular words and irregular words (e.g., yacht). Access to word meanings can occur when reading via the lexical route.

The dual route model supports the idea of a highly modular reading system. It suggests that to achieve successful reading, children need to master each of the modules (e.g. letter identification, grapheme-phoneme correspondence). An impairment in one or more modules leads to different subtypes of dyslexia (Castles, Bates, & Coltheart, 2006; Marshall, 1984). For example, difficulties with letter identification processes will lead to letter identification dyslexia (Brunsdon, Coltheart, & Nickels, 2006). Impairments in forming long-term memory representations of written words result in surface dyslexia (Friedmann & Lukov, 2008; Kohnen et al., 2018). Difficulties with learning grapheme-phoneme correspondences causes phonological dyslexia (Larsen et al., 2018).

The idea of dyslexia subtypes is relevant for research as well as clinical practice. According to a cognitive neuropsychological approach, training programs should focus on the impairments that characterise a child's subtype of dyslexia (e.g., Kohnen, Nickels, Castles, Friedmann, & McArthur, 2012; Kohnen, Nickels, & Coltheart, 2010).

While there is some evidence that training matched to a child’s impairment is more effective than

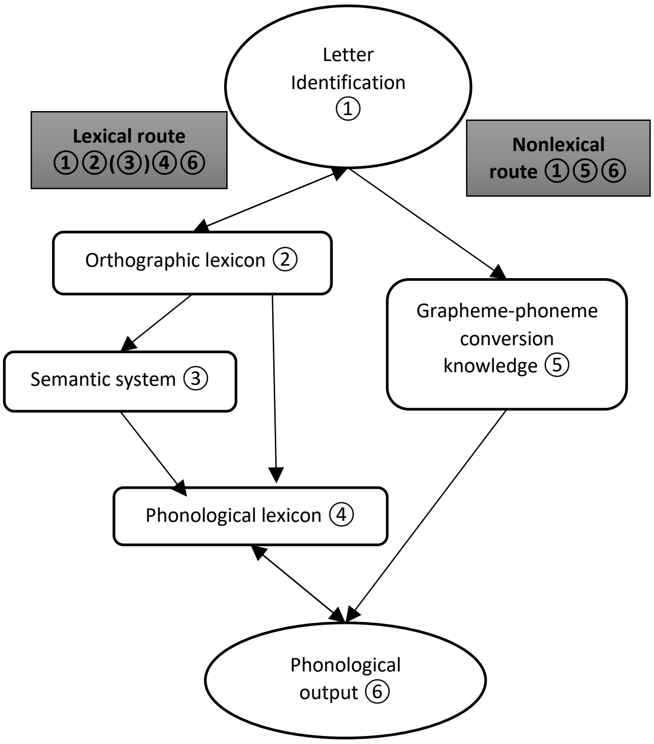

Figure 1. *The dual route model (Coltheart et al., 2001)*

training multiple reading skills (Gustafson, Ferreira, & Ro, 2007), relatively few intervention studies to date have examined the effects of specific reading interventions with specific reading impairments (Broom & Doctor, 1995a, 1995b; Friedmann & Rahamim, 2014; Gustafson et al., 2007). Instead, most intervention studies have used "omnibus" interventions that train multiple reading skills (M. W. Lovett, Karen, & Frijters, 2000; M. W. Lovett, Lacerenza, Palma, & Frijters, 2012; M. Lovett, Wolf, Sevcik, & Frijters, 2008; Morris et al., 2012; Savage, Georgiou, Parrila, & Maiorino, 2018). While such studies are admirable in catering for the diverse needs of the heterogeneous population of children with dyslexia, they require children to spend time training reading skills that are not necessarily impaired.

Another aspect of intervention that needs consideration is whether an intervention focuses on proximal or distal causes of dyslexia. A proximal cause is a component of the cognitive reading system that affects a reading behaviour directly and immediately (e.g. "breaking" a person's orthographic lexicon would immediately impair their ability to read known regular and irregular words). A distal cause has an indirect or delayed impact on reading (e.g. "breaking" a person's attention would impair their focus during reading instruction which would affect their ability to learn new words). McArthur and Castles (2017) and Galuschka, Ise, Krick, and Schulte-Korne, et al. (2014) argue that interventions that focus on proximal causes of dyslexic behaviour are more likely to be effective than interventions that focus on distal causes. To conclude, dyslexia is a highly heterogeneous disorder, which means that children with dyslexia need different types of treatment that focus on proximal causes of their impaired reading skills.

Visual attention span

It has been suggested that poor visual attention span is one proximal cause of developmental dyslexia (Lallier, Donnadieu, & Valdois, 2013). Many other causal hypotheses of dyslexia have been proposed as well (e.g., phonological hypothesis, magnocellular hypothesis, noise exclusion hypothesis). However, these are not the focus of the current investigation. Bosse, Tainturier and Valdois (2007) referred to visual attention span as the number of distinct visual elements that can

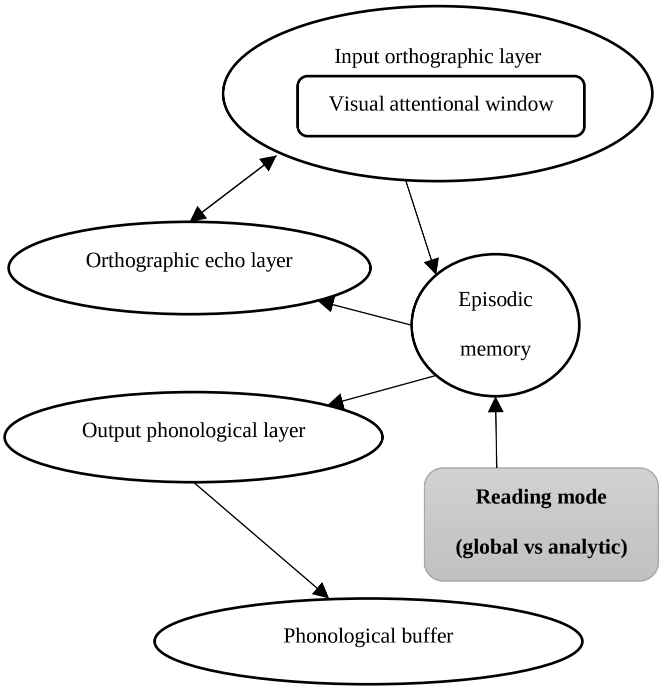

Figure 2. *The multitrace connectionist model of reading (Ans et al., 1998)*

be processed in parallel in a multi-element array. One model of reading that integrates visual attention is the connectionist multiple-trace memory model (Ans, Carbonnel, & Valdois, 1998).

According to this model (see Figure 2), reading relies on two types of procedures – global and analytic. In the global reading mode, the visual attention window extends over the whole letter array (word or phrase). This type of attention deals with familiar words and fails to process nonwords or unknown words. To read nonwords or unknown words the analytic mode is used – where the visual attention window narrows down and focuses on each letter successively.

The amount of distinct visual elements that can be processed in parallel in a multi-element array is called "visual attention span". According to the visual attention span deficit hypothesis (Bosse et al., 2007), visual attention span plays a significant role in reading. Specifically, impairments in the allocation of attention across letter arrays limits the number of elements that can be processed in parallel during reading. This, in turn, causes difficulties in processing multi-element strings, since one is not able to hold and process the whole letter string in the attentional window simultaneously, thus forcing reliance on the analytic reading mode. The reliance on reading letter-by-letter, in association with an impaired ability to read whole words, could be said to resemble the reading behaviours of surface dyslexia.

Bosse et al. (2007) tested their hypothesis that visual attention span deficit can be associated with developmental dyslexia independently of a phonological disorder. In two studies, they worked with relatively large samples of English- and French-speaking children (68 French native speakers with dyslexia, 55 age-matched controls; 29 English native speakers with dyslexia, 23 age-matched controls). In their first study (in French), they assessed children for (1) reading (irregular, regular and nonwords); (2) phonological awareness (phonemic segmentation, phoneme deletion and acronym tasks[1]); and visual attention span (global report of five letters in five-letter arrays, partial report of a single letter in five-letter arrays). As a group, children with dyslexia performed worse

[1] In this task participants had to extract the first phoneme of each presented word and blend them together to produce a new syllable (e.g., cat / [kæt]/ then eat / [iːt]/ → key [kiː]).

than controls on all of the reading tasks, on two of the phonological tasks (phoneme deletion and the acronym task), and on both visual attention span tasks. The authors reported positive correlations between measures of reading and phonological awareness (from .20 to .46), and between reading and visual attention span (from .49 to .69). They also reported that visual attention accounted for 29.4% of unique variance for irregular-word reading and 36.4% of unique variance for nonword reading.

In the second study (in English), Bosse et al. again assessed reading, phonological awareness and visual attention span in children. They also included tests for letter identification, semantic skills and phonological lexicon. The children with dyslexia were not significantly different from the control group for letter identification, semantics or the phonological lexicon. However, they performed significantly worse on all the reading, phonological awareness and visual attention span tasks. In this experiment, Bosse et al. also found correlations between reading and phonological awareness (from .28 to .61), and between reading and visual attention span (from .36 to .71). Based on these findings, the researchers concluded that both phonological and visual attention factors were significant and independent predictors of reading performance.

An eye-tracking study has provided further evidence supporting the visual attention span hypothesis. Prado, Dubois and Valdois (2007) compared 14 children with dyslexia and 14 typical readers on tests of visual search and reading. An eye-tracker was used to record participants' eye movements when performing the reading and visual search tasks. Prado et al. measured average fixation duration, number of fixations, and number of regressions (saccades that jump from right to left). They found no significant difference between the groups' eye-tracking metrics for the visual search task. In contrast, in the reading task the children with dyslexia made significantly more fixations and regressions than typical readers, and the duration of their fixations was longer than that of typical readers. The authors interpreted the results in light of the visual attention span hypothesis, suggesting that the children with dyslexia made smaller saccades and a larger number of fixations due to a narrow visual attention span that led to their reduced ability in processing multiple letters in parallel.

In sum, there are studies which suggest that children and adults with dyslexia as a group may have impairments in visual attention span. However, this evidence comes from correlation studies. Thus, it is not yet clear if reading and visual attention span impairments are causally related, are correlational, or are simply co-occurring.

Criticism of visual attention span hypothesis

Another uncertainty about the visual attention span deficit hypothesis is the extent of its scope. One might expect that a visual attention deficit affects the ability to process all visual stimuli. However, several replications of the Bosse et al. (2007) study have shown that participants with dyslexia struggle with reporting letter and digit strings but not with reporting symbol strings (e.g., Collis, Kohnen, & Kinoshita, 2013; Martelli, Di Filippo, Spinelli, & Zoccolotti, 2009; Ziegler, Pech-Georgel, Dufau, & Grainger, 2010). An impaired ability to report letter and digit strings has been referred to as a "multi-character deficit". Based on their findings, Ziegler et al. (2010) questioned the idea of a general visual attention deficit, suggesting that only elements that include symbol-sound mapping (letters and digits) are impaired. They further suggested that this impairment is not due to a multi-character processing deficit per se (i.e. an inability to process an array of letters or digits), but it rather reflects a phonological retrieval problem that impairs the ability to name letters and digits. However, there are several studies which indicate that this may not be the case (e.g., Lobier, Peyrin, Le Bas & Lobier, 2012; Lobier, Zoubrinetzky & Valdois, 2012). Importantly, for example, Peyrin et al., (2012) have shown that the neurobiological underpinning of the visual attention span is the superior parietal lobule, a region that has never been described as part of the phonological network.

In sum, there are studies which show that children and adults with dyslexia as a group have impairments with reporting letter and digit strings but not with reporting symbol strings. There are other studies which indicate that this impairment is not just a phonological retrieval problem.

However, it is not yet clear if the impairment is caused by a *general* visual attention span deficit or by another cognitive skill, responsible for processing alphanumeric elements.

Two cognitive impairments, other than a multi-character processing deficit, that might explain poor performance on multi-character processing tasks are poor visual short-term memory and poor visual working memory. Visual short-term memory is the ability to store visual information for a short period of time (e.g., remembering a mobile phone number read from a list of paper in order to write it down elsewhere). Impaired visual short-term memory capacity has been reported in dyslexic populations (Di Filippo, Zoccolotti, & Ziegler, 2008; Dubois et al., 2010). Poor visual short-term memory could impair performance on global and partial multi-character processing tasks by affecting the number of items that can be held in memory simultaneously. However, the relationship between visual short-term memory and multi-character processing has yet to be tested.

Similar to visual short-term memory, visual working memory has also been reported to be impaired in readers with dyslexia (Dubois et al., 2010; Rayner, 2009). Visual working memory refers to the ability to retain visual information for a short period of time while also manipulating this information (e.g., reading several numbers and calculating their sum). Poor visual working memory capacity can affect processing of multi-character elements, since one not only needs to remember the string of characters, but also to orally report it. Thus, a deficit in visual working memory may cause difficulties with partial and global report tasks. However, the relationship between multi-character processing and visual working memory has yet to be tested.

To summarise, there are two open questions regarding the visual attention span hypothesis. First, it is unclear, whether multi-character processing is part of visual attention span. It has also been suggested, that a deficit in multi-character processing might be caused by impairments in phonological retrieval, visual short-term memory or visual working memory. Second, it is unclear whether this deficit is causally related to reading. If multi-character processing is indeed part of visual attention span and has a causal effect on reading, then intervention studies that improve this impairment should similarly demonstrate reading improvements.

Multi-character processing intervention studies

While many studies have shown a concurrent impairment in reading and multi-character processing, few have tested directly if there is a causal relationship between the two impairments. Niolaki and Masterson (2013) carried out an intervention study for a multi-character processing deficit in a Greek child with dyslexia. Before the intervention, the child showed impairments in processing of multi-character letter strings (i.e., poor performance on a global report task), reading accuracy and fluency for words and texts. The intervention aimed to improve letter report accuracy, which the researchers suggested could be a possible cause of dyslexia. A global report task for letters was used during the intervention. The child was asked to orally report multi-letter strings presented briefly on a screen. Three sets of three- four- five-letter strings were created for the training program. The child practiced every day, ten minutes per day for nine weeks with a seven-day break in the middle of the intervention. The study employed a double baseline design plus posttest design for the global report task. While there were no significant gains during the untrained baseline period, after the intervention global report for letter strings was significantly better than prior to training. In addition, scores on tests of single word reading fluency and accuracy were higher after the intervention than before - even though reading had not been trained specifically.

A limitation of this study was the absence of control data for the reading tasks. Thus, pre- to posttest gains in the reading measures (single word reading accuracy and fluency) might have been due to test-retest effects or general maturation rather than an effect of improved multi-character processing on reading. Overall, the child’s single word reading fluency and accuracy remained significantly worse than that of the controls after the intervention. Niolaki and Masterson concluded that the deficit in multi-character processing was associated with the child’s literacy difficulty, but were careful to state that that they did not have enough evidence to pinpoint the possible mechanisms underlying the improvements. Nevertheless, they did suggest that intervention may have broadened an attentional window that was atypically small prior to training (forcing a slower non-lexical reading strategy), thus allowing greater lexical reading of whole words after the intervention. Another question, which Niolaki and Masterson have not investigated in their study, is whether multi-character processing is a part of visual attention span, they only used letter global and partial report to measure multi-character deficit.

The results of the study show unambiguous evidence that global report for letters has improved significantly after the intervention, although the question of multi-character processing causal relationship to reading, and its connection to visual attention span hypothesis requires further investigation.

Another relevant intervention study was performed by Valdois et al. (2014). Before the intervention, their participant, a bilingual French-Spanish speaking girl, MP, showed a severe reduction of reading fluency for words and texts in the two languages, and impairments in visual processing of multi-character strings (she was tested for letter and digit global and partial report). Valdois et al. proposed that the cause of their participant's impaired reading behaviour was a visual attention span deficit and designed an intervention aimed to improve it. The intervention included all visual attention span related stimuli (i.e., drawings, shapes, symbols, letters, multiple-element strings, using the visual attention span intervention programme "COREVA"). The training lasted for eight weeks with a-two-week break after the first three weeks, six days per week, 15 minutes per day.

The study included two types of controls: age-matched bilingual controls were tested and a double baseline plus posttest was conducted for all the reading assessments. In order to reduce test-retest effects, the authors selected different items for the reading tasks which were carefully matched for important psycholinguistic variables. In order to assess improvements in visual attention span, the authors conducted test once before and twice after the intervention using letter arrays and once before and once after the intervention using digit arrays. Carefully matched control participants were also tested on the same tasks.

After the intervention, global and partial report for letter and digit strings was higher than before the intervention. In addition, while MP's performance on both tasks was below control levels before the intervention, it was at control level after the intervention. However, since there was no double baseline for this task, it is not possible to completely rule out the possibility that this improvement was driven by other factors than the intervention (repeated testing, maturation, etc.)

The authors point out that for most reading tasks, there were improvements prior to the intervention (i.e., during the double baseline period). Valdois et al. describe the improvements from the second pretest to the first posttest as stronger than during the baseline period for regular and irregular word reading accuracy and fluency in French, for text word reading accuracy (per minute) in both French and Spanish. The girl with dyslexia reached the controls level at reading speed for regular words in French and at number of words read correctly per minute in Spanish. While these results look promising, additional statistical analyses to compare MP's performance across time, would allow to confidently rule out alternative explanations for the higher scores at posttest. Without statistical analyses confirming the visual analyses, it is possible that the improvements were not reliably higher after the intervention than during the baseline period.

Valdois et al. suggest that increasing the attentional window after the intervention resulted in a switch from nonlexical to lexical processing since more elements could be processed simultaneously during reading. It is also possible that improvements in reading fluency after the intervention might have been observed due to amelioration of retrieval speed of letters and digits phonological codes from long-term memory, however, this possibility was not taken into consideration by Valdois et al.

It is also important to note that in this study, visual attention span was only assessed with global and partial report tasks for letters and digits. In contrast, symbols were not included. This is also true for the Niolaki and Masterson study. In order to differentiate between the possibility of an improvement in visual attention span versus multi-character processing, the inclusion of symbols is important.

In summary, while studies by Valois et al. and Niolaki and Masterson show that scores on reading measures improved after interventions that focussed on the letter global report and general visual attention span trainings, methodological issues prevent us from being able to draw firm conclusions about a possible causal relationship. Both studies suggest that a narrow attentional window might have caused impaired reading behaviour, however, neither study assessed the visual attention span with all visual elements. Without measuring symbols as well as letters and numbers, the deficit may be in multi-character processing rather than in visual attentional span more generally. While it seems that letter global report and general visual attention span trainings (which includes letter global report as one of the exercises) can both improve children's ability to report letter arrays, what is less clear is if it has any effect on their reading behaviour, and what possible mechanisms may drive this relationship.

Current Study

This study focussed on a multi-character processing intervention for an English-speaking child with dyslexia. In order to find out whether a multi-character processing impairment may cause dyslexia, we replicated previous intervention studies by Niolaki and Masterson and Valdois et al. We also improved some of the methods: we conducted a double baseline for reading measures, spoken language measures, multi-character processing and other cognitive skills, which might influence poor multi-character processing (rapid automatized naming to test phonological retrieval speed, short-term memory and working memory to test possible influence of visuo-spatial memory span on letter strings report). Lastly, we included partial and global report tasks for digits, letters and symbols.

The study was designed to answer the following research questions:

Question 1: Can multi-character processing be trained?

To answer this question, we designed a four-week intervention that focussed entirely on global report of letter strings. We assessed letter string processing three times: twice before and once after the intervention. Based on previous intervention studies, we expected that letter reporting should improve significantly after the intervention (Niolaki & Masterson, 2013; Valdois et al., 2014). We also measured eye movement behaviour during reading to test if the child with dyslexia in this study made smaller saccades and a larger number of fixations as would be predicted given a narrow attention window (Bosse et al., 2007).

Question 2: Can multi-character processing training improve reading?

To assess whether multi-character processing has any causal effect on reading, we tested all component skills of reading according to the dual route model twice before and once after the intervention. Significant improvements after the intervention in any of the measures would provide evidence for a causal effect of multi-character processing on reading.

Question 3: Can multi-character processing training improve other cognitive skills?

To see whether expected improvements in multi-character processing for letters may cause general improvements of visual short-term memory or visual working memory, we assessed both these cognitive skills twice before and once after the intervention. Significant improvements after the intervention would provide evidence for general amelioration of these cognitive processes related to reading, rather than visual attention span.

To see if our intervention may have an effect on retrieval speed of phonological codes from long-term memory, we assessed rapid automatized naming (RAN) for letters, digits and colours. We hypothesised that if the improvement in letter and digit strings global report, observed in the previous studies, might have occurred due to general amelioration of retrieval speed of phonological codes, we should see an improvement in the global report tasks along with improvements on the RAN tasks. We tested rapid automatized naming for letters, digits and colours twice before and once after the intervention.

Question 4: Is the multi-character processing deficit a result of a general visual attention span deficit?

To answer this question, we assessed letter, digit and symbol strings processing twice before and once after the intervention. Only the letter global report task was trained. If an improvement of the global letter report task co-occurred with digit global report and symbol global report, this would support the idea that the multi-character processing deficit is part of a general visual attention span deficit. If an improvement of the global letter report task co-occurred with digit global report but not symbol global report, this would support the idea of a multi-character processing deficit is not part of a general visual attention span deficit. There also might be a third possibility – that a multi-character deficit is specific to just letters in dyslexia (i.e., a multi-letter deficit). If it was so, we should observe improvements in global report tasks only for letters.

Methods

Ethics statement

The methods used in this study were approved by the Macquarie University Human Ethics Committee (Ref: 5201300197). With their parent or guardian's consent, participants received $15 per hour of testing and $10 for travel expenses for each testing session. Parents and guardians were given an individualised report detailing the results of the assessment for their child.

Participants

There were two types of participants: (1) a control group consisting of typical readers,[2] and (2) an individual child with dyslexia who had a deficit in multi-character processing. All children were recruited via a participant recruitment website at Macquarie University: the Neuronauts register (https://www.ccd.edu.au/services/neuronauts/). Children were considered for the control group if they (1) were in grade 3, (2) had no history of reading or other learning difficulties, (3) had no history of psychiatric illness, (4) used English as their primary language. There were 6 female participants and 1 male participant (mean age = 8 years 9 months, SD = 2.85 months). Our case study child, YR, was 8 years and 10 months old at the time of her first visit for this study. YR had previously been assessed at the Macquarie University Reading Clinic, and had received 20 weeks of reading intervention. At this assessment, YR was essentially a non-reader. During the intervention YR was mainly trained on letter identification, grapheme-phoneme conversion knowledge and blending. After the intervention at the Macquarie University Reading Clinic, YR had learned to successfully identify and sound out 28 letters and letter combinations and had started to read small passages of decodable text. YR was monolingual English, right-handed, had no known motor, psychiatric, neurological, speech or oral language development problems, or any other diagnoses. There was no family history of reading difficulty.

[2] Here and elsewhere we refer to typical readers as those whose reading scores fall between (and including) the 16th to 84th percentile.

General procedure

Three assessment sessions were conducted during this study: baseline 1 (BL1)[3], baseline 2 (BL2), and post training (PT). We also used some diagnostic data from a prior assessment conducted by the Macquarie University Reading Clinic (MURC) a year before this intervention in order to reduce overall testing time. There was a period of four weeks between BL1 and BL2. The intervention, which also lasted four weeks, was only administered to YR, and took place between BL2 and PT. YR was tested at BL1, BL2 and PT. Controls were tested at BL1 and PT (to see general maturation of typical readers on the outcome measures).

The first testing sessions (BL1) lasted about 100 minutes for controls and 180 minutes for YR (there were two separate testing sessions at BL1. Participants were assessed within two weeks, each assessment session lasted 50 minutes for controls and 90 minutes for YR). The second testing session (BL2) with YR lasted about 120 minutes. The last testing session (PT) took place immediately after YR finished her intervention and lasted 120 mins for YR and about 80 minutes for controls (see Table 1 for the assessments timeline). All the testing sessions took place in a quiet testing room at Macquarie University. Testing was conducted by the author - IF. All testing sessions were recorded, scored by IF, and then double scored by IF's principal supervisor - SK. Any mismatches in scores were settled in discussions between IF and SK. The intervention took place at home on a computer, under the supervision of YR’s parents. It was conducted five days per week for 10 minutes per day.

Profiling measures

These measures were administered to YR in order to help characterize her reading and spoken language skills.

[3] There were two separate testing sessions at baseline 1, participants were assessed within two weeks.

Reading Measures

Letter identification accuracy and fluency

Letter identification knowledge was tested using a version of the cross case matching task, inspired by a subtest from the Psycholinguistic Assessments of Language Processing in Aphasia (LIDT; see Brunsdon et al., 2006[4]; PALPA; Kay, Lesser, & Coltheart, 1996). The experiment was created via MATLAB release R2012b (The MathWorks, Natick, MA, USA) using PsychToolbox version 3.0.10 revision 3187 (Kleiner et al., 2007). Items were presented in Courier New bold font (25 pt) in black on a white background. Participants were sitting approximately 70 cm away from a computer screen (1920 x 1080 pixel resolution). Each individual character subtended .63 x .63 degrees of visual angle (width x height). There were two practice trials before the experimental stage where children received feedback. At the beginning of each trial, children were presented with a fixation cross in the centre of the screen for 500 milliseconds, followed by a target letter in the middle of the screen (e.g., A). There were two more letters presented in the lower left (e.g., a) and lower right (e.g., v) corners. Participants had to choose which of two letters on the bottom matched the one in the middle of the screen by pressing the corresponding button. All letters of English alphabet were used in the task (except for upper case C, K, P, U, W, X, Y, Z, lower case p, s, v, w, x, y, z). The conditions were counterbalanced (both upper case and lower case letters were used as target letters 16 times). Participants had to choose which of two letters on the bottom matched the one in the middle of the screen by pressing the corresponding button. Children were instructed to press the correct button on the keyboard as quickly as they could. Children pressed a button marked as "left" with their left index finger and a button marked as "right" with their right index finger. Each button was clearly marked on the keyboard and children did not have to move their heads or look down to find the buttons. Instead, their index fingers of both hands were resting on them before the beginning of the test. After 3000 milliseconds, items disappeared. To

[4] The paper version of the LIDT test can be found on http://www.motif.org.au/

assess fluency, we measured the sum of reaction times for all items; to assess accuracy we summed items marked as correct (1 for each item).

Grapheme-phoneme correspondence knowledge

To test YR's ability to sound out single letters and letter combinations, we used the Letter Sound Test (LeST; Larsen, Kohnen, Nickels, & McArthur, 2012) which is designed for children in the first four grades of primary school. This test consists of 51 graphemes (e.g. t, er) that children are asked to "sound out". The inter-rater reliability of the test is high r = .95, as is the test-retest reliability r = .84 (Wang, Marinus, Nickels, & Castles, 2014). Each item was marked as correct (1) or incorrect (0). The number of correct items (out of 51 total number of items) was summed and converted into a standardized z-score that has a mean of 0 and SD of 1. We converted the obtained standardized z-score[5] into a percentile score.

[5] Z-score is a measure of how many standard deviations below or above the population mean a raw score is. Z-scores range from -3 standard deviations (which would fall to the far left of the normal distribution curve) up to +3 standard deviations (which would fall to the far right of the normal distribution curve), average z-score range falls between -0.67 +0.67 standard deviations.

Table 1. *Tests Assessment Timeline*

Cognitive skill (see Figure 1)	Test name	Measures		YR				Controls	
		Profiling	Experimental	MURC	BL1	BL2	PT	BL1	PT
	Reading Measures								
① Letter Identification	Letter Identification Test (LIDT) (accuracy, fluency)	v	v		v	v	v	v	v
⑤ Grapheme-phoneme correspondence knowledge	Letter-Sound Test (LeST) (accuracy)	v	v		v	v	v		
②③④ Lexical route	Irregular words reading (CC2) (accuracy)	v			v			v	
	Irregular words reading (accuracy, fluency)		v		v	v	v	v	v
⑥ Nonlexical route	Nonwords reading (CC2) (accuracy)	v			v			v	
	Nonwords reading (accuracy, fluency)		v		v	v	v	v	v
② Orthographic lexicon	Test of Orthographic Choice (TOC) (accuracy)	v	v		v	v	v		
	Woodcock Reading Mastery Test (fluency)	v			v			v	
	Neale Assessment of Reading Ability (accuracy, comprehension)	v			v			v	
	Text reading (accuracy)		v		v	v	v		
	Spoken Language Measures								
⑥ Phonological output	Blending words (from CTOPP)	v		v					
⑥ Phonological output	Nonword repetition (from NEPSY)	v		v					
④⑥ Phonological lexicon – phonological output	Fluency subtest (from PhAB)	v			v				
③④⑥ Semantic system - phonological lexicon – phonological output	Picture naming (from ACE)	v			v				
③ Semantic system	Squirrel-Nut Test	v			v				
	Other cognitive skills								
	Rapid automatized naming (CTOPP-II) (letters, fluency)		v		v	v	v	v	v
	Rapid automatized naming (CTOPP-II) (digits, fluency)		v		v	v	v	v	v
	Rapid automatized naming (CTOPP-II) (colours, fluency)		v		v	v	v	v	v
	Global report (letters, accuracy)		v		v	v	v	v	v
	Global report (digits, accuracy)		v		v	v	v	v	v
	Global report (symbols, accuracy)		v		v	v	v	v	v
	Partial report (letters, accuracy)		v		v	v	v	v	v
	Partial report (digits, accuracy)		v		v	v	v	v	v
	Partial report (symbols, accuracy)		v		v	v	v	v	v
	Visual short-term memory (accuracy)		v		v	v	v	v	v
	Visual working memory (accuracy)		v		v	v	v	v	v
	Eye movements behaviour		v		v	v	v	v	v

Note. MURC - Macquarie University Reading Clinic; LIDT - adapted from the Psycholinguistic Assessments of Language Processing in Aphasia by Brunsdon et al., 2006; Lest by Larsen et al., 2012; CC2 - the Castles and Coltheart Test by Castles et al., 2009; Irregular Word Reading by McArthur et al., 2015; Nonword Reading adapted from Test of Word Reading Efficiency by Torgesen et al., 1999; TOC by Kohnen et al., 2012; the Woodcock Reading Mastery Test by Woodcock, 2011; the Neale Assessment of Reading Ability by Neale, 1999; CTOPP - the Test of Phonological Processing by Wagner et al., 1999; NEPSY - the Developmental Neuropsychology Assessment battery by Korkman et al., 1998; PhAB - Phonological Assessment Battery by Frederickson, et al., 1997; ACE - the Assessment of Comprehension and Expression by Adams et al., 2001; Squirrel-Nut Test by Pitchford & Eames, 1991; CTOPP-II - Comprehensive Test of Phonological Processing by Wagner et al., 2013;

CC2 nonword and irregular word reading accuracy

We measured lexical and nonlexical reading using the Castles and Coltheart Test (CC2; Castles et al., 2009) which was designed for children aged 6-12 years. The CC2 nonword reading subtest assesses nonlexical reading, that is, the ability to use letter-sound rules to read aloud (e.g., “SPATCH”). The CC2 Irregular word subtest assesses lexical reading using words that cannot be read accurately using the letter-sound rules alone (e.g., “YACHT”). The CC2 also includes a regular word subtest which assessed reading accuracy for regular words (e.g., “PLANT”) but these scores were not used in this study. There were 40 nonwords, 40 regular words, and 40 irregular words printed separately on flashcards and administered in a semi-randomised order of increasing difficulty (e.g., nonword 1, regular word 1, irregular word 1, irregular word 2, regular word 2, nonword 2, and so on). Children were asked to read each item aloud. The assessment of each word type (e.g., nonwords) was stopped after 5 consecutive errors. Each item was marked as correct (1) or incorrect (0). The number of correct items in each list was summed and a z-score assigned based on the normative data provided for Australian primary school children (Castles et al., 2009). We converted the obtained standardized z-score into a percentile score. The CC2 has good internal consistency reliability, reported Cronbach’s alpha was 0.94 for the nonword subtest, 0.86 for the irregular and 0.85 for the regular word subtest (Moore, Porter, Kohnen, & Castles, 2012).

Orthographic lexicon

To test YR’s orthographic lexicon, we used the Test of Orthographic Choice (TOC; Kohnen, Anandakumar, McArthur, & Castles, 2012). The TOC consists of 30 test items and two practice items. In this test, a child sees a word-nonword pair. One word is the correct spelling (e.g. door) and the other one its alternative homophonic spelling (e.g. doar). The child has to choose which of the two items is spelled correctly. Each item was scored as correct (1) or incorrect (0). The scores were summed and converted into a percentile score. Test–retest reliability is good, r = .57, as reported in a previous study (Wang et al., 2014).

Text reading fluency

We assessed oral text reading fluency using the Woodcock Reading Mastery Test (WRMT-III; Woodcock, 2011). In this test, children were asked to read two grade-appropriate passages. Two measures were taken: time to complete each passage and number of errors made while reading each passage. To measure fluency, the number of reading mistakes was subtracted from the number of words in the passage, then divided by the number of seconds taken to read the passage and multiplied by 60. The results for two passages were summed and converted into a percentile score. The internal consistency reliability of the test is very high (r=.99), and test-retest reliability ranged from .51 to .95 based on the age (Woodcock, 2011).

Neale text reading accuracy and comprehension

We measured text reading accuracy and comprehension with the Neale Assessment of Reading Ability (NARA; Neale, 1999) designed for children aged 6 to 12 years. This standardised test consists of a training passage and six reading passages of increasing length and difficulty. Children were asked to read the texts aloud. After each passage, children were asked comprehension questions (6-8 questions for each passage), which they answered verbally. Testing discontinued after 16 accuracy mistakes made on any of the first five passages, or twenty accuracy mistakes made on the sixth passage. Comprehension questions were only asked if the test was not discontinued. A score for text reading accuracy was based on the child's reading accuracy of the passages (a given amount of scores per passage, e.g., 16, minus the number of mistakes made during reading, e.g., four). A score for text reading comprehension was based on the child's ability to answer the questions (for each question answered correctly a child received 1 point, 0 for an incorrect answer). Scores were converted into standard scores, which were then converted into a percentile score. The internal reliability of the accuracy subtest ranges from $.91 \leq r \leq .96$, and the comprehension subtest ranges from $.71 \leq r \leq .96$ (Neale, 1999).

Spoken language measures

Phonological output

YR's phonological output was measured prior to this study by the Macquarie University Reading Clinic using two tests. In the Blending Nonwords subtest from the Test of Phonological Processing (CTOPP; Wagner, Torgesen, & Rachotte, 1999), YR listened to 20 nonwords of increasing length and phonological complexity separated into phonemes and was asked to put all the phonemes together to form a nonword. Each item was scored as correct (1) or incorrect (0). The scores then summed and converted into a percentile score.

In the Nonword Repetition subtest from the Developmental Neuropsychology Assessment battery (NEPSY; Korkman, Kirk & Kemp, 1998), YR was asked to repeat 46 spoken nonwords (e.g., PHLENTISH) of increasing length played from an audio device. The scores then summed and converted into a percentile score.

Semantic and phonological retrieval

To assess YR's retrieval of semantic and phonological information from a long-term memory, we used the Fluency subtest from the Phonological Assessment Battery (PHaB; Frederickson, Frith, & Reason, 1997) for children of 5-11 years old. YR was asked to say as many words of particular type as possible in one minute. There were three parts to this test: (1) naming things to eat, (2) naming words beginning with /b/, and (3) words that rhyme with *more*. Each word was marked as correct (1) or incorrect (0). The scores were summed and converted into percentile scores.

YR's retrieval of semantic and phonological information was also assessed with the Picture Naming subtest from the Assessment of Comprehension and Expression (ACE; Adams et al., 2001) designed for children of 6-11 years. There are 25 pictures in the subtest which YR had to name orally. Each answer was marked as correct (1) or incorrect (0). All the scores were summed and converted into a percentile score.

Semantic knowledge

To measure YR's semantic knowledge, we used the Squirrel-Nut Test (Pitchford & Eames, 1994). This test consists of 57 triads of pictures. For example, an owl may appear in the middle of the page with pictures of the sun and moon in the left bottom and right bottom positions respectively. Children are asked to point to the picture that is semantically linked to the picture in the middle of the page (moon is linked to an owl, because it is a nocturnal animal). Each item is marked as correct (1) or incorrect (0), the scores were calculated from the sum of all correct items. Normative comparison data were available for YR's age group (Pitchford & Eames, 1994).

Outcome measures

These measures were collected twice pre- and once post- training in order to answer our research questions.

Multi-character processing

Multi-character processing global and partial report tasks were created via MATLAB release R2012b (The MathWorks, Natick, MA, USA) using PsychToolbox version 3.0.10 revision 3187 (Kleiner et al., 2007). The strings presented consisted of five letters or digits, with each character within the string separated by a single character space. Characters were presented in Courier New font (18 pt) in black on a white background. Each individual character subtended 0.39 x 0.39 degrees of visual angle (width x height), for a total string width of 3.51 degrees.

There were familiarization trials in each condition. Each child could complete as many trials as needed to understand the task, and feedback was given during the familiarization phase. At the beginning of each trial, children were presented with a fixation cross in the centre of the screen for 500 milliseconds, followed by a five-character string for 200 milliseconds, and then a post-mask (five "?" symbols) which remained on the screen until the answer was given. In the global condition children had to orally report the items (as was previously done by Niolaki & Masterson, 2013; Valdois et al., 2014). In the partial report condition, the ten response options were displayed on the screen (as was previosly done by Schubert, Badcock, & Kohnen, 2017). Children had to orally report a letter/digit and the experimenter (the author, IF) clicked on the reported item.

Global report

There were 20 experimental trials. Children had to orally report as many letters/digits (see below) as they could. Each reported letter/digit was then marked as correct (1) or incorrect (0). The order of report did not need to match their position in the string. The maximum score participants could receive for the task was 100.

Partial report

There were 50 experimental trials. One of the post-mask positions was underscored and turned red, children had to orally report a letter/digit (see below) in that position. Each reported letter/digit was then marked as correct (1) or incorrect (0). The maximum score for the task was 50.

Letters

In the global and partial letter tasks, strings of five letters were displayed. The strings were built using the following 10 consonants (B, P, T, F, L, M, D, S, R, H). Each letter occurred once within a string. After creating all of the items, the trials were randomized. This same randomised order of trials was used for YR at BL1, BL2, PT and for controls at BL1, PT.

Digits

In the global and partial digit tasks, strings of five digits were displayed. The strings were built up from 10 digits (1, 2, 3, 4, 5, 6, 7, 8, 9, 0). Each digit only occurred once within a string. The trials were randomized once, the same order of trials was used for YR at BL1, BL2, PT and for controls at BL1, PT.

Eye movements behaviour

We used eye-tracking technology to test if a multi-character processing deficit is reflected in atypical eye movements, as reported in previous studies (Prado et al., 2007). We presented shortened versions of 21 grade-appropriate reading passages from the Visualizing and Verbalizing Series (Earl, Jones, Spaulding, & Sweeney, 2006) while participants' eye movements were recorded with an EyeLink 1000 tower mount system (from SR Research Company) with a sampling rate of 1000 Hz. Texts were presented on a Samsung S27A950 screen with a 1920 x 1080 pixel resolution and 120 Hz refresh rate. Each reading passage consisted of 48-54 words and was presented in four lines in black 16.5 pt Courier New bold font on a white background. Each letter subtended .36 x .36 degrees of visual angle, and each line subtended 26.3 degrees of visual angle in width.

Participants were seated 90 cm away from the screen with their head rested on a forehead- and a chin-rest. A nine-point calibration routine was performed before text reading commenced. Prior to each passage, a fixation point was presented in the left upper corner of the screen, where the first line of text began. Testing started with the presentation of three familiarization passages, followed by a short break before the experimental run, and another short break in the middle of the experimental run (after 9 text passages). Children were instructed to silently read the passages. After they finished reading, they pressed any button on the keyboard to proceed to the next passage. To ensure that children read the sentences, simple yes/no comprehension questions were presented on the screen after some of the passages (8 comprehension questions in total). Children pressed a button marked as "yes" with their right hand and a button marked as "no" with their left hand. Each button was clearly marked on the keyboard and children did not have to move their heads or look down to find the buttons. Instead, their index fingers of both hands were resting on the keys before the beginning of the test.

To score the eye-movements, we excluded the first and last words in each line of each passage, and the words surrounded by any sort of punctuation to avoid abnormal fixations around the end of clauses or sentences (Rayner, Kambe, & Duffy, 2000).This left around 35 words from each passage for analysis:

~~In China, a~~ dog named Lele buys his own ~~food.~~

~~Lele~~ barks when he is hungry and his owner gives him ~~money.~~

~~Then~~ he runs to a nearby market with the bill in his ~~mouth.~~

~~Lele~~ drops ~~the bill, grabs~~ the sausages and runs back home with ~~them.~~

We also excluded all fixations shorter than 50 milliseconds (which is a common practice, see Rayner, 1998).

It is noteworthy that YR's reading was so impaired that she was only able to read the first passage of the 21 passages. Thus, while controls read all 21 passages, only data from the first passage was used for statistical comparison.

We used the available eye-movement data to calculate metrics. First, we calculated *average fixation duration*, which is the mean amount of time that a reader's eyes focus on each word across the first passage we used for analysis. This was used as an index of how easily information could be processed in a fixation. Children in the third grade usually make fixations about 262-286 milliseconds in duration (Rayner, 1998). Longer fixation durations are often reported in dyslexic population (Judica, De Luca, Spinelli, & Zoccolotti, 2002; Thaler et al., 2009).

Second, we calculated *average saccade amplitude*, which is the mean distance the eyes travel from left-to-right between fixations on words across all passages. This is thought to reflect overall processing difficulty of a text. Typical readers normally move the eyes forward 7-9 characters on a given saccade. Readers with dyslexia usually make shorter saccades compared to normal readers (Kowler, 2011).

Third, we calculated *number of fixations*, which is the mean number of fixations that the eyes make per passage. This metric helps to understand whether long reading time is due to long fixation durations or their amount (Prado et al., 2007).

Fourth, we calculated *number of regression*s, which is the mean number of times that the eyes make saccadic jumps to the left. Increased number of regressions is associated with postlexical integration difficulties. Making lots of regressions is also a distinctive feature of dyslexic population (Judica et al., 2002).

Fifth, we measured *first fixation duration*, which is the duration of the first fixation on a word. First fixation durations is usually associated with prelexical stages of word recognition, such as early orthographic processing (Hawelka, Gagl, & Wimmer, 2010; Korinth & Fiebach, 2018).

Finally, we indexed *first-pass reading time* which is the sum of all fixation durations on a word after a fixation enters and before leaving the word. First-pass reading times is thought to be an indicator of lexical access or decoding (Rayner, 1998).

Reading measures

Letter identification accuracy and fluency

We used the same version of the cross case matching task (see above, profiling measures – reading measures – letter identification accuracy and fluency) to assess a possible improvement of YR's letter identification knowledge.

Grapheme-phoneme correspondence knowledge

We used the Letter Sound Test (LeST; Larsen et al., 2012) (see above, profiling measures – reading measures – grapheme-phoneme correspondence knowledge) to assess YR's ability to sound out single letters and letter combinations.

Irregular word reading accuracy

We assessed a possible improvement of YR's irregular word reading accuracy with a bespoke test. The irregular word reading accuracy test used a list of 30 items from a previous study (the "trained items" from McArthur et al., 2015). Children read aloud all the irregular words printed individually on flashcards. Each item was marked as correct (1) or incorrect (0). Children's scores were calculated as the sum of all items read correctly.

Nonword reading accuracy

We assessed a possible improvement of YR's nonword reading accuracy with a bespoke test. The nonword reading accuracy test used the first 42 nonwords from the Test of Word Reading Efficiency (TOWRE, form A; Wagner, Torgesen, & Rashotte, 2013). Children read aloud all the items printed individually on flashcards at their own pace. Each item was marked as correct (1) or incorrect (0). Children's scores were the sum of all items read correctly.

Irregular word reading fluency

We assessed lexical reading fluency using 30 irregular words there matched in frequency to the irregular words used in the irregular word reading accuracy test described above (the "untrained items" from McArthur et al., 2015). The list was printed out on an A4 paper, with words equally distributed between two columns presented in Arial font (20 pt). Before starting the test, children were given a practice list, which consisted of eight irregular words. Children were asked to read as many irregular words aloud as possible in 45 seconds. Each item was then marked as correct (1) or incorrect (0). Children's scores in the subtest were calculated by the sum of all items read correctly.

Nonword reading fluency

We assessed nonlexical reading fluency using a list of the first 42 nonwords from the Test of Word Reading Efficiency (TOWRE, form B; Torgesen, Wagner, & Rashotte, 1999). The list was printed on a single piece of paper, with words equally distributed between two columns presented in Arial font (20 pt). Before starting the test, children were given a practice list, which consisted of eight nonwords. Children were asked to read as many nonwords aloud as quickly as they could in 45 seconds, with each item marked as correct (1) or incorrect (0). Children's scores in the subtest were calculated by the sum of all items read correctly.

Orthographic lexicon

We used the Test of Orthographic Choice (TOC; Kohnen, Anandakumar, et al., 2012) (see above, profiling measures – reading measures – orthographic lexicon) to test for a possible improvement of YR's orthographic lexicon.

Text reading accuracy

We assessed YR's text reading accuracy with a bespoke test that comprised two grade-appropriate reading passages. YR read the passages aloud, and each word read was marked as correct (1) or incorrect (0). YR's score was the sum of words read correctly.

Other cognitive skills

Phonological retrieval for letters, digits, numbers

We used rapid automatized naming (RAN) subtests for letters, digits and colours from the Comprehensive Test of Phonological Processing (CTOPP II; Wagner et al., 2013) to measure how fast participants could scan the arrays of visual symbols and retrieve phonological information from long-term memory. Each subtest consisted of 36 items. An individual's score was the total number of seconds taken to name all the items in a subtest. This was converted into a percentile score for letters and digits. Since in CTOPP II colours rapid automatized naming subtest only has normative data for children up to 6 years of age, we did not report a percentile score for this task, but only compared YR to controls on this task. Thompson et al. (2015) report a good reliability, $r = .75$ for letters and digits subtests tests.

Memory measures

Short-term memory

We assessed non-verbal visuo-spatial short-term and working memory using a bespoke version of the Corsi Blocks Forward and Backward Span task. Children were presented with nine white cubes placed on a blank board. There was a number printed on each cube which faced the experimenter, while the child could not see them.

Short-term memory was assessed with the Forward Span task, in which the experimenter tapped a series of cubes consecutively, ranging from two taps to seven taps. There were three series per number of taps (i.e., a total of 15 series). Children were asked to tap the same cubes in the same order. There was no stopping rule. For each cube tapped correctly, children received a point (1). For incorrect or forgotten tap, children received 0 points. The maximum score for this task was 60.

Working memory

The procedure in the Backward Span task was the same as the Forward Span task except a child was asked to tap the blocks in the reverse order tapped by the experimenter.

Visual attention span

To assess the outcome measures of visual attention span we used global and partial report tasks for letters and digits (see above, outcome measures – multi-character processing) and for symbols.

Symbols

In these tasks, strings of symbols were displayed. The strings were built up from 10 symbols (!, @, #, $, %, ^, &, *,), -), each item only occurred once within a string. Once the strings of symbols were created, we randomized them once. This same randomised order of trials was used for YR at BL1, BL2, PT and for controls at BL1, PT. In the symbols report condition, the ten response options were displayed on the screen (as previosly done by Schubert et al., 2017). Children had to orally report a string of symbols/ a symbol and the experimenter (the author) clicked on the item. Children were told that they could point to the keyboard if they did not know the symbol names, but all of the participants consistently used the same made up names for symbols instead (e.g., % was called “eyes and nose”, # – “hashtag”, ^ - “arrow up”).

Intervention

Only YR completed the intervention. The intervention procedure for YR involved repeated practice at reporting letter strings of increasing length. The procedure for the presentation was exactly as described for the global report task in the Methods section. For the intervention, we created 40 sets of strings: sets 1-10 consisted of 100 two-letter strings, sets 11-20 consisted of 100 three-letter strings, sets 21-30 consisted of 100 four-letter strings, sets 31-40 consisted of 100 five-letter strings. These strings were presented in order of increasing difficulty in practice sessions that lasted approximately 10 minutes per day, and took place at home under supervision of YR's parent. There were 5 practice sessions per week, and the intervention lasted for 4 weeks.

The intervention program was created via MATLAB release R2012b (The MathWorks, Natick, MA, USA) using PsychToolbox version 3.0.10 revision 3187 (Kleiner et al., 2007) and performed on Macbook Pro (15-inch, 2011) laptop (1680 x 1050 pixel matte screen resolution). YR borrowed a laptop from the Macquarie University Department of Cognitive Science for the intervention. All the data was automatically recorded on the laptop. Parents were contacted daily to report on progress, and to discuss and solve any difficulties.

Results

The results are divided into three sections. In the first, we describe a diagnosis of YR's profile, which we established with a combination of tests administered at baseline 1 (BL1)[6] and by the Macquarie University Reading Clinic prior to this study. In the second section, we present YR's performance during the four weeks of intervention as evidence or treatment integrity. In the third section, we compare YR's performance on the outcome measures compared to herself across the three testing points (BL1, BL2, PT), and her performance on the outcome measures compared to the control group at BL1 and PT.

Diagnosis of YR's profile

A dual route model-based diagnosis

Table 2. *YR's profiling measures results*

DRC Model-based Skill (see Figure 1)	Test Name	Max Score	YR	
			Raw Score	Percentile
	Reading measures			
① Letter identification	Letter Identification Test - accuracy*	32	21	-
① Letter identification	Letter Identification Test – fluency*	-	73.7	-
⑤ Grapheme-phoneme correspondence	Letter-Sound Test	51	28	1
①②③④⑥ Lexical route	CC2 Irregular word reading accuracy *	40	5	2
①⑤⑥ Nonlexical route	CC2 Nonword reading accuracy *	40	2	3
② Orthographic lexicon	Test of Orthographic Choice	30	16	6
	Spoken language measures			
⑥ Phonological output	Blending words	20	13	63
⑥ Phonological output	Nonword repetition	46	34	63
③④⑥ Semantic system - phonological lexicon - phonological output	Semantic fluency	-		30
④⑥ Phonological lexicon - phonological output	Alliteration fluency	-		58
④⑥ Phonological lexicon - phonological output	Rhyme fluency	-		90
③④⑥ Semantic system - phonological lexicon - phonological output	Picture naming	25	14	25
③ Semantic system	Squirrel-Nut Test	57	57	-

Note. We used previously published measures where possible and report YR's percentile scores based on these norms. *Comparisons were made to controls, see Table 5.

[6] There were two testing sessions in baseline 1, participants were assessed within two weeks

YR had severe impairments in letter identification. She could only match 21 out of 32 letter trials in the Letter Identification Test (see Table 2). In contrast, controls were almost at the ceiling on this task (M = 29.3 SD = 1.6). Her poor letter identity knowledge is also reflected in her severely impaired reading performance on all other reading tests, in which YR would sometimes misidentify letters.

YR also showed deficits in her grapheme-phoneme correspondence knowledge. She could only provide sounds for 28 out of 51 graphemes in the Letter-Sound Test, while average readers at her age typically know at least 40 grapheme-phoneme correspondences. YR's poor knowledge of grapheme-phoneme correspondences was also reflected in her performance when reading nonwords on the CC2 test. YR could only read 2 nonwords correctly out of 40, while the control children[7] read 28 nonwords on average (M = 28.3 SD = 4.3). The process of reading words or nonwords in YR's case rarely consisted of reading an entire word. Instead, she mostly proceeded letter by letter, sounded out familiar letters, then sometimes corrected to produce a digraph (e.g., "s, h, sh") and blend them into words. This very laborious letter-by-letter process would sometimes be successful but often not.

YR's poor performance on the Test of Orthographic Choice indicated that her orthographic lexicon was severely impaired. YR was only able to identify correctly 16 words out of 30 pairs, which meant her performance was at the 6th percentile for her age. Consistent with an impaired orthographic lexicon, YR's irregular word reading on the CC2 test was also severely impaired. She was able to read 5 irregular words correctly, while controls read 24 words on average (M = 24.2 SD = 3.7).

Given YR's poor reading of single words and nonwords, it was not surprising that her text reading accuracy, fluency and comprehension were also impaired. Text reading tests (Woodcock Reading Mastery Test III; Neale Assessment of Reading Ability; NARA) confirmed that YR had few sight

[7] All our controls scored ≥25 percentiles on all reading tests.

words in her orthographic lexicon, sounding out (letter-by-letter) even very frequently occurring words such as “and”. YR scored ≤ 1 percentile on WRMT-III, ≤ 1 percentile on NARA accuracy subtest, and was at the 7th percentile on the NARA comprehension subtest.

Interestingly, YR's performance on all of the spoken language tests was within the average range for typically developing children (≥ 16 percentile on all the tests). Her performance on the Squirrel-Nut Test showed that her semantic system was intact. Typical performance on Picture Naming and Semantic Fluency tests show that the connections between semantic system, phonological lexicon and phonological output were developing normally. Alliteration Fluency and Rhyme Fluency subtests revealed that YR’s phonological lexicon and phonological output connections were also not impaired (see Table 2).

Thus, YR is best described as having letter identification dyslexia. Her inability to master this initial step in the reading process affected all subsequent steps, making the task of reading extremely challenging. In addition, YR’s performance was characterised by a letter by letter reading strategy. She attempted almost all words letter by letter, not even recognising the most common and short words (e.g., and, if). Even digraphs (e.g., sh) were often sounded out as their component letters first (i.e., s, h, sh).

Outcome measures-based diagnosis

Table 3. *YR’s outcome measures results.*

Cognitive skill	Test Name	Max score	YR	Controls, N=7
Multi-character processing	Global report task (letters)	100	10	52.8 (15.2)
Multi-character processing	Global report task (digits)	100	26	62.8 (8.1)
Multi-character processing	Partial report task (letters)	50	10	15.6 (5)
Multi-character processing	Partial report task (digits)	50	7	18.6 (6.8)
Visual attention span	Global report task (symbols)	100	14	42.4 (10.4)
Visual attention span	Partial report task (symbols)	50	8	13.3 (6.1)
Eye movements behaviour	Average fixation duration (ms)	-	117	205.6 (33)
Eye movements behaviour	Average saccade amplitude (degree)	-	0.77	3.95 (0.6)
Eye movements behaviour	Fixations count	-	698	41.4 (8.6)
Eye movements behaviour	Number of regressions	-	65	6.4 (5.2)
Eye movements behaviour	1st fixation duration (ms)	-	108	209.5 (56)

Eye movements behaviour	First-pass reading (ms)	-	411	258.6 (63)
Phonological retrieval speed of visual stimuli	Rapid automatized naming (letters, s)	-	42.5	19.4 (2.3)
Phonological retrieval speed of visual stimuli	Rapid automatized naming (digits, s)	-	83	18.3 (2.2)
Phonological retrieval speed of visual stimuli	Rapid automatized naming (colours, s)	-	67	31.8 (3.7)
Visual memory	Visual short-term memory	60	49	54 (5.5)
Visual memory	Visual working memory	60	48	53.1 (4.6)

Note. Here we only report raw scores at BL1 on all the outcome measures, statistical analysis of the outcome measures is presented in Tables 5,6. This table is used to demonstrate YR's diagnosis

YR's performed significantly worse than controls on global report tasks for letters and digits (see Table 3), indicating that she has a multi-character processing deficit. YR's performance in the global report task for symbols was impaired, same as for letters and digits (see Table 3). It took YR 42.5 seconds to complete letter automatized naming, 83 seconds to complete digit automatized naming subtest. Moreover, it took YR 67 seconds to complete colour automatized naming subtest. The fluency tests described above showed that YR's ability to retrieve phonological information from long-term memory was intact. It is possible, that the poor RAN performance may indicate that she had difficulty retrieving verbal output information from visual input. YR did not show any impairments on the short-term memory and working memory tests, her results were at control level (see Table 6).

One might suggest that a child with letter identification difficulties, such as YR, would perform poorly on the global letter report task because they misidentify the letters, rather than due to the fact that they cannot process the typical amount of characters simultaneously. For YR we believe that she, like so many children with dyslexia, had multiple deficits. One problem was indeed her ability to recognise letters accurately and another deficit was to process multiple characters simultaneously. YR's letter by letter strategy when reading words (described above) was also reflected in her eye-tracking data which showed that she could only analyse two spaces at a time (see Table 3, average saccade amplitude - 0.77 degrees of visual angle at BL1. Each letter subtended on .36x.36 degrees of visual angle). In YR's reading attempts, letter identification was not always, but very often, accurate. If her poor score on the global report task was only driven by her poor ability to identify letters, then we would expect YR to report as many letters as the controls, albeit the reported letters would be inaccurate (e.g., reporting a B instead of an R). This was not the case. Prior to the intervention, YR could only report one letter per array in half of the trials, possibly reflecting that she could, at most, process one letter within the string at any one time. In fact, YR did not actually know how many letters were in the array. She reported: “I cannot see them. It’s too quick.” In contrast, the controls always reported five letters, even though the letters were not always correct.

Thus, in addition to the theoretical questions addressed in this thesis, moving away from YR’s letter-by-letter processing to processing multiple characters simultaneously was also a practical intervention goal.

YR's performance during the intervention

YR started her training with the two-letter sets. In order to move up to the next level of sets (e.g., to three-letter strings), she needed to reach an accuracy level of at least 75% items reported correct in at least one set. On day 3 of intervention, YR reported accurately 83.5% of two-letter string (167 letters out of 200) and hence moved to sets of three-letter strings on the fourth day of intervention. She immediately dropped down to 51% accuracy. YR found the three-letter strings very difficult and did not reach the accuracy criterion to move up to the next set. Instead, she completed all ten sets of the three-letter strings, with accuracy ranging from 49% to 61%. In day 4 of Week 3, YR started to practice with four-letter strings. Her performance dropped below 50% (see Table 4) and she found the task extremely difficult. Nonetheless, she finished the intervention as planned.

Table 4. *YR’s target accuracy during the intervention*.

	Week 1			Week 2			Week 3			Week 4		
	Set No	Length	% accurate	Set No	Length	% accurate	Set No	Length	% accurate	Set No	Length	% accurate
Day 1	1	2	73	13	3	50	18	3	49	23	4	43
Day 2	2	2	74	14	3	49	19	3	54	24	4	40
Day 3	3	2	83.5	15	3	55	20	3	55	25	4	46
Day 4	11	3	51	16	3	50	21	4	42	26	4	44
Day 5	12	3	55	17	3	61	22	4	41	27	4	40

Note. Set No = the number of a set (1-40) used for practice; Length = the length of letter strings in the set; % accurate = percent of letters reported correctly

YR's performance on the outcome measures

To analyse the effect of treatment, we conducted two analyses. First, we used Weighted Statistics (WEST; Howard, Best, & Nickels, 2015), which comprises two parts. The first was used to examine whether there was a statistically significant difference over the course of the study using WEST-Trend. If there was an overall improvement over the three testing points (BL1, BL2, and PT), we analysed if this improvement coincided with the treatment period using the WEST-Rate Of Change (WEST-ROC) analysis, which tested if the rate of change was greater during the treatment than the no-treatment phases. We only concluded that a treatment effect was present if both WEST-Trend and WEST-ROC were significant (see Table 5). In the second analysis, we compared YR's performance to a control group at BL1 and PT using modified t-tests (SINGLIMS; Crawford et al., 2001). This allowed us to investigate if her performance moved closer to control levels at the end of the study (see Table 6).

The outcomes of the WEST-Trend and WEST-ROC analyses are shown in Table 5.

The outcomes of the SINGLIMS analysis are shown in Table 6.

Table 5. *Results of YR's weighted statistics examining the trend across the study (WEST-Trend) and comparison of rate of change between baselines and post training (WEST-ROC). Significant results are bolded. A treatment effect required both WEST-Trend and WEST-ROC analyses to be significant.*

Test Name	Total items	YR			WEST-Trend		WEST-ROC	
		BL1	BL2	PT	t	p	t	p
Multi-character processing								
Global report letters	100	10	17	46	6.99	**.000**	3.49	**.000**
Global report digits	100	26	17	39	2.56	**.010**	4.46	**.000**
Partial report letters	50	10	9	9	-0.30	.620	0.12	.450
Partial report digits	50	7	3	3	-1.43	.920	0.81	.210
Visual attention span								
Global report symbols	100	14	21	29	4.68	**.000**	0.18	.430
Partial report symbols	50	8	7	7	-0.37	.650	0.23	.410
Eye movements behaviour								
Average fixation duration (ms)	-	117	158	242	3.00	**.000**	2.24	**.020**
Average saccade amplitude (degree)	-	0.77	0.76	1.43	4.32	**.000**	2.29	**.010**
Fixations count	-	698	-*	457	-	-	-	-

Number of regressions	-	65	-*	87	-	-	-	-
First Fixation duration (ms)	-	108	128	260	3.00	**.000**	2.24	**.020**
First-pass reading time (ms)	-	411	736	513	1.86	.200	-1.96	.970
Reading measures								
Letter identification (accuracy)	32	21	23	22	1.16	.130	0.37	.360
Letter-Sound Test	-	28	20	31	1	.160	2.56	**.010**
Irregular word reading (accuracy)	30	1	4	2	0.57	.290	-1.31	.090
Nonword reading (accuracy)	42	19	22	16	-0.90	.810	-1.39	.910
Nonword reading (fluency)	42	4	8	8	3.12	**.000**	-1.71	.940
Test of Orthographic Choice	30	16	19	15	-0.3	1	1.83	**.040**
Text reading (accuracy)	60	27	34	35	1.82	**.040**	-0.95	.830

Note. *Data collection is interrupted after 5 minutes of testing, we report the results obtained at BL1, PT and do not analyse these two measures. **Results for rapid automatized naming are explained below.

Question 1: Can multi-character processing be trained?

In order to answer this question, we analysed the results for the global report task for letters and digits. YR's global report for letters was significantly higher after the intervention than before intervention (see Table 5). At BL1 YR's results on the letter global report were significantly different from controls, although at PT, YR's results were no longer significantly different from controls (see Table 6). Her digit global report improved significantly after the intervention (see Table 5), although it did not reach control level accuracy (see Table 6).

We also assessed YR's eye movements behaviour during silent text reading. YR's average fixation duration became significantly longer after the intervention (see Table 5), but had not improved to control level (see Table 6). YR's average saccade amplitude, average fixation duration and first fixation duration improved significantly. Her average saccade amplitude at pretests (see Table 5) was equal to two spaces in text, after the intervention it significantly enlarged and became equal to four spaces. Although YR's average saccade amplitude remained significantly different from our control group (see Table 6).

Table 6. *YR's intervention measures results compared to a control group using modified t-tests (SINGLIMS; Crawford & Garthwaite, 2002). Significant results are bolded.*

Test Name	Total Item	YR		Controls (N=7, N=5*)		SINGLIMS			
		BL1	PT	BL1	PT	BL1		PT	
						t	p	t	p
Multi-character processing									
Global report letters	100	10	46	52.8 (15.2)	63.7 (9.6)	-2.64	**.019**	-1.73	.067
Global report digits	100	26	39	62.8 (8.1)	69 (9.5)	-4.24	**.002**	-2.95	**.012**
Partial report letters	50	10	9	15.6 (5)	19.1 (8.4)	-1.05	.167	-1.12	.152
Partial report digits	50	7	3	18.6 (6.8)	21.3 (8.7)	-2	.082	-1.94	.051
Visual attention span									
Global report symbols	100	14	29	42.4 (10.4)	48 (6.5)	-2.56	**.021**	-2.71	**.021**
Partial report symbols	50	8	7	13.3 (6.1)	14.4 (6.4)	-0.79	.227	-1.08	.160
Eye movements Behaviour*									
Average fixation duration (ms)	-	117	242	205.6 (33)	205.9 (23)	-2.441	**.036**	1.408	.116
Average saccade amplitude (degree)	-	0.77	1.43	3.95 (0.6)	4.1 (0.6)	-4.838	**.004**	-4.062	**.008**
Fixations count	-	698	457	41.4 (8.6)	28.8 (6.1)	71.608	**.000**	64.081	**.000**
Number of regressions	-	65	87	6.4 (5.2)	3 (1.1)	10.638	**.000**	69.71	**.000**
First Fixation duration (ms)	-	108	260	209.5 (56)	205.3 (21)	-1.655	.087	2.39	**.038**
First-pass reading time (ms)	-	411	513	258.6 (63)	233.5 (27)	2.463	**.035**	9.606	**.000**
Reading measures									
Letter identification (accuracy)	32	21	22	29.3 (1.6)	30.7 (1.3)	-5.05	**.001**	-6.26	**.000**
Letter identification (fluency, s)	-	73.7	66.5	45.8 (10.4)	39.5 (6.8)	3	**.024**	3.66	**.005**
Irregular words reading (accuracy)	30	1	2	23 (3.7)	22.8 (2.9)	-6.9	**.000**	-6.73	**.000**
Nonwords reading (accuracy)	42	19	16	37.1 (3.6)	35.7 (4.3)	-4.70	**.002**	-4.29	**.002**
Nonwords reading (fluency, 45 s)	42	4	8	34.5 (5.9)	34 (4)	-4.83	**.001**	-6.08	**.000**
Other cognitive skills									
Phonological retrieval (RAN, letters, s)	-	42.5	43	19.4 (2.3)	19.4 (2.4)	2.67	**.018**	9.19	**.000**
Phonological retrieval (RAN, digits, s)	-	83	46	18.3 (2.2)	17.5 (2.3)	27.94	**.000**	11.59	**.000**
Phonological retrieval (RAN, colours, s)	-	67	100	31.8 (3.7)	32 (4.5)	19.18	**.000**	14.21	**.000**
Visual short-term memory (accuracy)	60	49	52	54 (5.5)	55 (2.6)	-0.85	.213	-1.08	.160
Visual working memory (accuracy)	60	48	53	53.1 (4.6)	56.1 (2.5	-1.05	.168	-1.16	.145

Note. * There were 5 controls for this part of the study

We could not provide a double baseline for fixations count and the number of regressions, since data collection at BL2 was interrupted after 5 minutes of testing due to equipment failure. However, the first fixation duration, first-pass reading times, average fixation duration and average saccade length are still informative. Especially the first two measures (the first fixation duration and first-pass reading time), which are first-pass reading measures, and YR managed to read the passage at least three times (three passes) before interruption. From the data obtained during BL1 and PT, it appears that YR needed at least five passes to finish reading. Therefore, we only compare YR's number of fixations and regressions for BL1 and PT with our control group. YR performed significantly worse than controls both at BL1 and at PT (see Table 6), there was no improvement observed in these two measures.

YR's first fixation duration changed significantly (see Table 5). At BL1 YR's first fixation duration was significantly different from controls, at PT her first fixation duration was no longer significantly different from the control group (see Table 6). YR's first-pass reading time did not change significantly after the intervention (see Table 5) and remained significantly worse than that of controls (see Table 6) both at BL1 and at PT.

Question 2: Can multi-character processing training improve reading?

None of the measures which we used to test YR's reading skills according to the dual route model showed significant improvements after the intervention. YR performed significantly worse on all the assessed tasks than our control group both before (BL1) and after the intervention (PT) (see Table 6).

Question 3: Can multi-character processing training improve other cognitive skills?

Neither YR's scores on visual short-term memory, nor her scores on visual working memory were significantly lower than those of controls (see Table 6) prior to the intervention, and no significant changes were observed in these two measures after the intervention. At PT, YR was still performing at control level.

As for the rapid automatized naming performance[8], YR's results on letters remained the same through all testing sessions (42,5 seconds at BL1, 43 seconds at BL2, 43 seconds at PT), and slowed on colours (67 seconds at BL1, 79 seconds at BL2, 100 seconds at PT). Her naming speed on digits improved steadily across the three test points (83 seconds at BL1, 69 seconds at BL2, 46 seconds at PT). In order to estimate if this was a significant change, we analysed the estimated z-score difference for digit rapid naming between BL1, BL2 and PT scores, which was .53. This does not constitute a significant difference between pre- and posttest ($p=0.23$, 1-tailed). Thus, we did not observe a reliable improvement on any of the rapid automatized naming tasks. YR's performance remained in the impaired range (<10 percentile) on all rapid automatized naming tasks at all time points.

Question 4: Is the multi-character processing deficit a result of a general visual attention span deficit?

To answer this question, we analysed YR's performance on the global report tasks for letters, digits and symbols. Her letter and digit global report improved significantly after the intervention (see Table 5), although only the performance on letter report reached control level accuracy (see Table 6). YR's symbols global report did not change significantly (see Table 5). YR's performance on partial report task did not change significantly for any of the tested items (see Table 6). However, YR's partial report abilities also did not differ significantly from that of controls at any test point (see Table 6).

[8] Please note that the RAN task cannot be analysed using Weighted Statistics. Weighted Statistics require accuracy or response time data for each item. We did not have by-item response times for the RAN task and accuracy was at ceiling.

Discussion

This study aimed to determine (1) whether multi-character processing can be trained; and if so, (2) can it lead to improvements in reading and (3) other cognitive skills. We further aimed to investigate whether training of multi-character processing improves visual attention span in order to answer (4) a question regarding its origins.

Question 1: Can multi-character processing be trained?

Our results clearly show that YR's global report for letter strings improved significantly after the intervention. This outcome is in accordance with Niolaki and Masterson's (2013) result. The noteworthy part is that it took YR only four weeks to complete the training program, in comparison with the previous study's nine weeks. We also observed a significant improvement in the digit report task immediately after the intervention. Thus, our findings provide further evidence in support of previous studies, which indicated that some adults and children with dyslexia show specific deficit for processing letters and digits (Collis et al., 2013; Ziegler et al., 2010).

We also assessed YR's eye movements during silent text reading. According to our data, letter global report training resulted in longer average fixation duration, first fixation duration and average saccade amplitude. Unfortunately, we could not provide a double baseline for the number of fixations and regressions, since data collection at BL2 was interrupted after 5 minutes of testing due to equipment failure. However, the first fixation duration, first-pass reading times, average fixation duration and average saccade length are still informative, especially the first two measures, which are first-pass reading measures, and YR managed to read the passages at least three times (three passes) before the interruption.

In a previous study, Hawelka and Wimmer (2005) indicate that increased number of fixations during reading is consistent with the idea that a multi-character processing deficit is reflected in the number of elements processed simultaneously. Since we could not provide sufficient data for the number of fixations and regressions during BL2, we report the obtained data for BL1 and PT to underline just how impaired these two measures were in comparison to controls (see Table 5). Our training did not seem to improve either the number of fixations nor the number of regressions for YR. Thus, multi-character processing is clearly not the only cognitive skill reflected by the fixation count or number of regressions.

Moving, then, to the global eye movement measures, eye movements during more developed silent reading are characterized by longer saccades, shorter fixations, fewer fixations, fewer regressions and a higher skipping rate as compared to less developed silent reading (Korinth & Fiebach, 2018). In line with this, our data indicated that multi-character training resulted in YR making longer saccades (from 0.77 to 1.43 degrees of visual angle). In contrast, this training also resulted in longer fixations (from the initial 117 milliseconds to 242 milliseconds after intervention). Nevertheless, it is worth noting that in typically-developing reading, fixations range from 200-225 milliseconds for adult readers and 262-286 milliseconds for children, increasing when text is more difficult and decreasing, when text is comparatively easy (note that our control group showed the average fixations of 205.9 milliseconds, which indicates that the assessed reading passage was comparatively easy, see example above, outcome measures – multi-character processing – eye movements behaviour). In comparison, YR fixated on words for abnormally short periods of time (about 117 milliseconds) prior to the intervention, suggesting that her reading was extremely atypical for her age. However, after the intervention, her fixations and saccades lengthened, becoming closer to normal readers.

It is possible to interpret YR's eye-movement results within a model that links eye-movements to reading. Hawelka, Gagl and Wimmer (2010) were the first to attempt to link letter and word reading with eye movement behaviours by mapping the dual route model of single word reading with E-Z Reader. model of eye movement control during silent reading (see Figure 3). We will interpret the obtained results within this model.

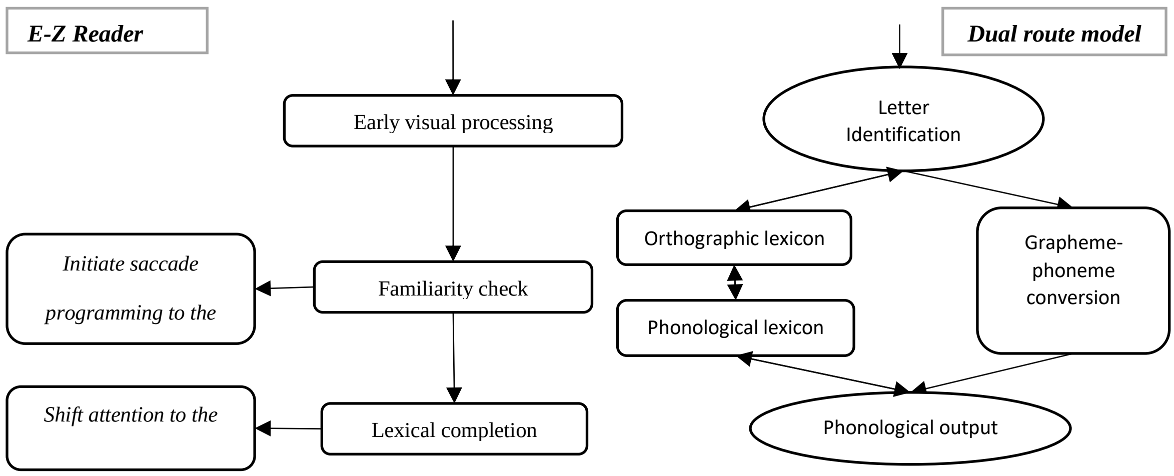

Figure 3. *E-Z Reader and Dual route model*

According to the E-Z Reader, early visual processing occurs during the first fixation, which corresponds to letter identification processes in the dual route model. At the initial assessment, YR showed abnormally short first fixation durations (108 milliseconds, compared to 210 milliseconds in control group, see Table 6), which reflects her impaired letter identification processes. In accordance with Hawelka et al.'s findings, YR fixated at the beginning of words and formed abnormally short forwarded saccade amplitudes (saccade amplitude was 0.77 on average, which means YR moved her eyes on two spaces). While her average fixation duration was abnormally short at the beginning of the study (about 117 milliseconds), she exhibited much increased first-pass reading time (about 410 milliseconds).

As shown by previous studies (Mackeben, Adler, & Klosinski, 2004), frequent orthographic recognition failures result in a general tendency of readers with dyslexia to target the beginning of a word, and thus rely on nonlexical route and read using grapheme-phoneme conversion. YR shows a similar reading behaviour: Her increased number of fixations, together with abnormally short fixation durations, might indicate her inability to successfully complete the letter identification processes and "move" forward to the later cognitive processes that need to be completed to successfully read a word.

The intervention resulted in YR's improvement of the first fixation duration (260 milliseconds) and average fixation duration (242 milliseconds), suggesting that her general eye movement behaviour became somewhat closer to being typical. Her saccade amplitude increased (to 1.43 degrees of visual angle, which is equal to four spaces), as well as her first-pass reading time (513 milliseconds, not statistically significant, see Table 6). This might indicate that YR was able to come as far as to "familiarity check" (see Figure 3), where, again, not being able to rely on grapheme-phoneme correspondence knowledge, was forced to make another saccadic jump in attempts to find familiar letters. Our data might be indicating that before the intervention, YR's reduced ability to process multiple letters in parallel was impaired to the point where she simply could not find any familiar letters in her visual window. In contrast, after the intervention she could analyse 3-4 letters in parallel which resulted in longer fixations and more successful attempts to access the familiar letters in parallel. It is important to note that YR managed to complete her training in the global report task with four-letter strings, the eye tracking data showed that YR was able to immediately use her enlarged attentional window during reading task.

Unfortunately, the research of adults and children with dyslexia on eye movement behaviour during reading rarely differentiates existing subtypes of dyslexia, and if does, only refers to surface and phonological dyslexia. To our knowledge, there were no studies investigating eye movement behaviour of children with letter identification dyslexia. The abnormally short fixation durations might be a distinguishing feature peculiar to this subtype of reading disorder. The obtained results require further investigation.

Question 2: Can multi-character processing training improve reading?

In contrast to the study by Niolaki and Masterson (2013), we included a double baseline for all our experimental reading measures. Thus, we were able to determine if improvements were due to the intervention and not due to general maturation or test-retest effects. Our results suggest that there was no improvement in YR's irregular word reading accuracy or fluency, nonword reading accuracy or fluency, or text reading accuracy. In fact, YR's reading skills were all so impaired that she was not able to read a single irregular word within 45 seconds before or after the intervention. Her results in the Test of Orthographic Choice (where YR was presented with an irregular word and a matching nonword with alternative homophonic spelling) showed that amelioration of letter string report did not influence her ability to make the right choice in this task. These results suggest that the relationship between multi-character processing and reading is not causal, but co-occurring. It was suggested in the previous studies (see Valdois et al., 2014) that increasing the attentional window by intervention should result in a switch from nonlexical to lexical processing. The results of this study suggest that this is not the case.

It is also important to mention, that although YR's eye movements behaviour became more consistent with an expected "normal" pattern for eye movements during reading, it did not help her improve her reading abilities. Which might be another argument for YR having multiple co-occurring deficits. The results of our study suggest that she was able to increase the attentional window significantly after the intervention, but it did not help YR ameliorate her impaired letter identification processes.

In the profiling part of the study, we outlined that YR had a deficit both in letter recognition and in her ability to process multiple letters simultaneously. Given that YR did not improve on the letter identification task, the improvements on the global report task were not due to improved letter recognition skills. Instead, it is more likely that YR indeed learned to process multiple characters at the same time, which provides further evidence that the multi-character deficit may be an independent cognitive skill. YR did not only have difficulties identifying letters, but she also had difficulties processing multiple letters at the same time.

Question 3: Can multi-character training improve other cognitive skills?

To determine if expected improvements in multi-letter strings report might lead to better performance on visual short-term memory and/or visual working memory tasks, we assessed both these cognitive skills twice before and once after the intervention. Our results show that YR's visual short-term memory and visual working memory skills were at control level during the initial assessment and after the intervention (see Table 6). There were no improvements in these skills as a consequence of the intervention. Thus, improvements of multi-letter processing did not occur because of the general visual memory amelioration.

We assessed YR's rapid automatized naming for letters, digits and colours to see, whether multi-character processing skills might increase because of improvements in retrieval speed of visually presented phonological codes from long-term memory. We hypothesised that the reason of YR's improved scores in the letter global report task might be in general amelioration of retrieval speed of visually presented phonological codes. Before the intervention we established that YR did not have a phonological retrieval problem. This was indicated on the fluency tasks reported in the profiling section. However, YR performed significantly worse than our control group on letters, digits and colours rapid automatized naming tasks. This was interpreted as showing a difficulty in YR processing verbal output from visual input. The results of our study show that YR's performance on rapid automatized naming did not improve. Thus, her difficulty with retrieving phonological information from visual input does not seem to be causally related to the global report task. In other words, YR significant improvement in a letter global report was not due to easier access and faster retrieval speed of visually presented phonological codes from long-term memory, but rather an independent cognitive skill.

To summarise, our data showed that multi-character processing deficit is not related to general visual short-term or working-memory capacity, neither it is related phonological deficit (note, that YR did not have a phonological deficit per se, but rather a specific deficit of retrieving verbal output information from visual input).

Question 4: Is the multi-character processing deficit a result of a general visual attention span deficit?

If a multi-character processing deficit was a result of a general visual attention span deficit, we would expect that training visual attention span with any type of visual stimuli (in this case, letters) should improve global report of letters, digits, and symbols. Our results do not support this. While YR's global report for letters and digits was improved after intervention, this was not the case for symbols. Thus, our findings provide further evidence in support of previous studies (see Collis et al., 2013; Ziegler et al., 2010) that suggested that some people with dyslexia show specific deficits for processing letters and digits but not symbols, which reflects impaired multicharacter processing rather than impaired visual attention span. It would appear that YR's deficit in the global report of symbol strings before and after intervention was an independent co-occurring impairment.

Summary

As mentioned in the introduction, poor visual attention span has been suggested as one of the proximal causes of developmental dyslexia (Lallier et al., 2013). Previous interventions (Niolaki & Masterson, 2013; Valdois et al., 2014) have tested the idea that there might be a causal relationship between the impaired ability to process several letters in parallel and dyslexia. Although, there were several limitations in each of them, which did not allow researchers to provide firm evidence in support of causal relationship of multi-character processing to reading. Firstly, Niolaki and Masterson (2013) did not include a double baseline for the reading measures in their study, which did not allow them to demonstrate, that improvements in single word reading accuracy and fluency, and text reading fluency that they observed occurred because of their training and not because of general maturation or test-retest effects. Secondly, Valdois et al. (2014), could not actively test their hypothesis of visual attention span deficit as a causal reason of multi-character deficit and dyslexia, since they did not assess all the visual elements (e.g., symbols) to test the deficit, but only tested the child with dyslexia on multi- letter and digit strings, furthermore, they did not include a double baseline for the global report tasks.

We improved on methods of previous interventions, including a double baseline for all the outcome measures we assessed (reading skills, visual memory, phonological retrieval speed, strings of letters, digits, symbols) and using recent statistical analyses methods appropriate for the data. We also tested, whether multi-character deficit is a part of general visual attention span deficit by adding symbol strings as one of our outcome measures.

Despite our efforts to improve upon the design of previous studies that have tested the relationship between reading and multi-character processing or visual attention span, it still had a number of limitations which we summarise below.

We only tested YR immediately after the intervention. Thus, we could not observe any possible delayed impacts of our training on assessed skills. Future studies of multi-character processing should also focus on possible delayed effects of multi-character processing on reading in order to pinpoint the possible mechanisms, relating these two cognitive skills. However, as mentioned in the introduction, McArthur and Castles (2017), Galuschka et al. (2014) argue that interventions that focus on proximal causes of dyslexia are more likely to be effective than interventions that focus on distal causes. Therefore, even if multi-letter global report has delayed or indirect impact on reading, providing interventions that would focus on proximal causes of dyslexia would be more effective.

We had a training program for one child with dyslexia. Larger studies replicating our finding should be conducted to provide further evidence that (1) multi-character processing can be trained, (2) the training enlarges attentional window, allowing to process multiple letters in parallel and changing eye movements behaviour, (3) multi-character processing does not have any causal relationship to reading, (4) multi-character processing is a cognitive skill, which functions independently of general visual attention span.

Also, it is important to mention, that YR had a letter identification dyslexia, although children in the previous studies (Niolaki & Masterson, 2013; Valdois et al., 2014) both had surface dyslexia. Still, YR had multiple co-occurring deficits, one of which was processing of multiple characters simultaneously. Our practical intervention goal was to move away from YR's letter-by-letter processing to processing multiple characters simultaneously. Our data shows that after the training YR was able to analyse multiple letters in parallel.

To summarize, our intervention study actively tested the idea that there might be a causal relationship between multi-character processing deficits and dyslexia. We also tested whether multi-character processing is causally related to phonological retrieval of visually presented input, visual memory and visual attention span. We provided a double baseline for all the outcome measures and also assessed eye movement behaviour to see the changed pattern immediately after the training.

We have demonstrated that multi-character processing can improve significantly after training – our child with dyslexia became significantly better at reporting letter and digit strings, moreover, the eye movements during text reading task have also demonstrated significant change, supporting the idea, that letter global report intervention increases attentional window.

And still, we have not found any evidence supporting the existence of associations between dyslexia and impairments in multi-letter processing. More specifically, improvements in global letter report task did not have any immediate impact on dyslexia. This study also demonstrated that multi-character processing deficit can occur even when visuo-spatial short-term memory and working memory systems are intact. It functions independently of a phonological retrieval of visually presented stimuli deficit, otherwise we would have observed improvements in rapid automatized naming immediately after the intervention. It is not part of a visual attention span deficit since we did not observe any improvements in symbol global report performance after the intervention.

To conclude, this study has brought in new evidence of underlying mechanisms of multi-character processing. Specifically, our data are compatible with the idea that multi-character processing is not part of general visual attention span, visual short-term, working memory, or phonological retrieval of visually presented stimuli, but rather an independently functioning cognitive mechanism, responsible for processing multiple visually presented characters in parallel. This study demonstrates that intervention studies form a useful methodological tool in answering questions about causation in dyslexia.

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Appendix of this thesis has been removed as it may contain sensitive/confidential content