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Article

Double trouble – visual and phonological impairments in English dyslexic readers

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Abstract

Developmental dyslexia is a reading disorder characterized by problems in accurate or fluent reading. A deficiency in phonological processing is thought to underpin the reading difficulties of individuals with developmental dyslexia and a variety of explanations have been proposed including deficits to phonological awareness and verbal memory. Recent investigations have begun to suggest that developmental deficits in the acquisition of reading may also co-occur with visual processing deficits, which are particularly salient for visually complex stimuli, yet these deficits have received relatively little attention from researchers. To further explore the nature of phonological and visual processing in developmental dyslexia, we administered a series of non-reading tasks tapping both domains. Unsurprisingly, individuals with developmental dyslexia performed worse than typically developing readers in phonological tasks. More intriguingly, they also struggled with visual tasks, specifically when discriminating between novel visual patterns, and in visuo-spatial working memory which requires greater attentional control. These findings highlight that individuals with developmental dyslexia present not only with phonological impairments but also difficulties in processing visual materials. This aspect has received limited attention in previous literature and represents an aspect of novelty of this study. The dual phonological and visual impairments suggest that developmental dyslexia is a complex disorder characterized by deficits in different cognitive mechanisms that underpin reading.

Keywords: developmental dyslexia, DD; dual-route model, DRC; triangle model; visuo-spatial working memory, VSWM; visual processing.

Double trouble – visual and phonological impairments in English dyslexic readers

Developmental dyslexia (DD) is a neurodevelopmental disorder characterized by difficulties in reading aloud despite normal intelligence and adequate instruction (American Psychiatric Association., 2013). The cognitive basis of DD is thought to be a phonological deficit and, sometimes, this is proposed as the unique cause (Bruck, 1992; Ramus, 2001; Swan & Goswami, 1997; Vellutino, 2004). This view is widely accepted, and underpins one of the primary models explaining the reading disorder in DD, the Dual-Route Cascaded model, DRC (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001).

In this model, reading is assumed to involve two major processes, or "routes" (Figure 1). First, one can access stored word pronunciations in the phonological lexicon following activation from the orthographic lexicon or semantic system. This lexical process is necessary when reading words with ambiguous or irregular spellings such as *colonel*. Second, reading can occur via a sub-lexical grapheme-to-phoneme conversion process. In contrast to the lexical process, the sub-lexical process can generate plausible pronunciations for regular words or phonologically plausible non-words but will produce regularisation errors for irregular words (e.g., *colonel* -> "colernel"; *yacht* -> "yatched"; *sugar* -> "sudger").

Figure 1 about here

Although several subtypes of DD have been described (Castles, Bates, & Coltheart, 2006; Castles & Coltheart, 1993; Friedmann & Coltheart, 2016) there are two strands of evidence that point to some degree of independence between lexical and sub-lexical routes (Castles et al., 2006). First, developmental surface dyslexia is characterized by a difficulty in reading irregular words due to a deficit in the lexical route (Castles, 1996; Job, Sartori, Masterson, & Coltheart, 1984; Zoccolotti et al., 1999). Second, phonological dyslexia is

characterized by a difficulty in reading unfamiliar words or non-words due to a deficit in the phonological or sub-lexical route (Rack, Snowling, & Olson, 1992; Snowling & Hulme, 1989; Temple & Marshall, 1983).

Despite evidence indicating that impaired phonological processing represents the core deficit in DD, which may lie within these linguistic routes, there is little consensus regarding the specific mechanisms underlying lexical and sub-lexical processes and the heterogeneity of the difficulties presented by individuals with DD. In fact, there is evidence demonstrating that DD may also be characterized by a deficit in different domains, such as auditory and visual processing.

Many studies have demonstrated that some individuals with DD may present with an auditory deficit. For instance, impaired processing of brief sounds, which can affect speech perception in these cases (Fraser, Goswami, & Conti-Ramsden, 2010; Heiervang, Stevenson, & Hugdahl, 2002; Molinaro, Lizarazu, Lallier, Bourguignon, & Carreiras, 2016; Rey, De Martino, Espesser, & Habib, 2002; Tallal, 1980; Wright et al., 1997). Auditory deficits are somewhat independent from phonology, but nevertheless play a role in the severity of the observed phonological deficit (see Ramus, 2003 for an extensive literature review on this aspect).

More striking evidence of the heterogeneity of DD comes from studies that show not all individuals with DD manifest phonological impairments (Bosse, Tainturier, & Valdois, 2007; Jones, Branigan, & Kelly, 2008; Lobier, Zoubrinetzky, & Valdois, 2012). These findings raise the interesting possibility that different performance patterns might actually reflect distinct underlying mechanisms, rather than differences in the processes or relationships within and between the two routes (Lobier et al., 2012; Stein, 2018; Stein & Fowler, 1981; Valdois et al., 2003; Valdois, Bosse, & Tainturier, 2004).

Furthermore, individuals with DD may struggle to process visual stimuli, with some presenting with dysfunction in visuo-spatial attention (Stein & Walsh, 1997; Vidyasagar & Pammer, 2010). This is often present with an asymmetrical distribution of spatial attention in the two visual fields, such that one is unable to inhibit information from the right visual field and focus attention in the centre of gaze (e.g., Boden & Giaschi, 2007; Martin & Lovegrove, 1984). This pattern of difficulties may disrupt allocation of attention across letters and is generally attributed to a deficit of the magnocellular pathway, and in particular the dorsal pathway, which is involved in the analysis of motion perception (see e.g., Ramus, 2003 for a review of the magnocellular deficit in DD). However, despite evidence showing that the magnocellular deficit can contribute to DD, it remains a controversial and hotly debated issue. In fact, there is no clear evidence that a deficit in the magnocellular pathway can contribute to the reading difficulties in DD, independently of phonological impairments. Moreover, a deficit in the magnocellular pathway has been reported in the scenario of phonological dyslexia but not in surface dyslexia, leaving open the question of what causes this subtype of dyslexia (see e.g., Spinelli et al., 1997; Valdois et al., 2004).

Theories explaining deficits in visuo-attention span underpinning surface dyslexia have contributed to the debate with the most prominent of these being work by Bosse and colleagues (Bosse et al., 2007). The visuo-attention span hypothesis posits that difficulties in DD are a consequence of a deficit in visual processing. In this vein, the visuo-attention span hypothesis underpins the existence of a visual system impairment in this population (Frey & Bosse, 2018; Lobier et al., 2012; Zoubrinetzky, Collet, Serniclaes, Nguyen-Morel, & Valdois, 2016).

The visuo-attention span theory is derived from the connectionist multi-trace memory model of reading (Ans, Carbonnel, & Valdois, 1998) and postulates the existence of two reading procedures which are characterized by different "attentional windows" – the analytic

(serial) and global (parallel) procedures. The analytic mode uses a narrow attentional window or "spotlight" which serially processes orthographic sub-units (letters or letter combinations) within the word. During this mode, phonological outputs corresponding to each sub-unit are generated successively and have to be maintained in a buffer (memory trace) for phonological production. The global mode uses a wide attentional window or "floodlight" which permits automatic recognition or parallel processing of the whole word during reading aloud, and thus generates the entire phonological output without involvement of the buffer. In this framework, visual attention span is defined as the number of elements (letter units) processed simultaneously (Lallier & Valdois, 2012).

Familiar words are generally processed through the global mode, employing a wide visual attentional window, whereas unfamiliar words are processed through the analytic mode, employing a narrow attentional window – this is because more attention is needed to generate phonological representations from a combination of unfamiliar letter units. If the normal visual attention span is reduced, reading becomes reliant on the analytic mode. Due to the inability of this mode to generate the entire output, irregular word reading becomes slow and regularisation errors may occur. Hence, this theory is able to account for word recognition difficulties in one sub-group of individuals with DD independently of phonology, conceptualized as surface dyslexia, whereas word recognition difficulties in individuals with phonological dyslexia might be better captured by phonological deficits (Bosse et al., 2007; Lobier et al., 2012; Stefanac, Spencer-Smith, Brosnan, Castles, & Bellgrove, 2019; Valdois et al., 2003; Zoubrinetzky, Bielle, & Valdois, 2014; Zoubrinetzky et al., 2016).

Taken together, these findings support the claim that individuals with DD may present with impairments in the visual domain, that are not restricted to word processing. Studies investigating visual processing of non-orthographic stimuli (e.g., faces and objects) have indeed demonstrated atypical performance, which strengthens the hypothesis that a visual

impairment may characterize some types of DD (Gabay, Dundas, Plaut, & Behrmann, 2017; Robotham & Starrfelt, 2017; Sigurdardottir, Fridriksdottir, Gudjonsdottir, & Kristjánsson, 2018; Sigurdardottir, Ívarsson, Kristinsdóttir, & Kristjánsson, 2015). Such evidence cannot be fully accounted for by lexically-based visual word recognition models (i.e., the DRC model).

An alternative approach which might accommodate some of these findings proposes that disorders of reading do not occur in isolation but are an emergent effect of damage to one of three primary systems (vision, phonology, semantics), or damaged input to them, to which reading may be more susceptible (Hoffman, Lambon Ralph, & Woollams, 2015; Patterson & Lambon Ralph, 1999). The triangle model (Figure 2) is an instantiation of the primary systems hypothesis, and proposes that the same computational elements, in various combinations, support different reading and non-reading activities: (1) vision, which with respect to reading mediates knowledge about orthographic word form but also processes non-orthographic visual stimuli; (2) phonology – the internal representation of word sound, also utilized by any form of verbal input or output including naming and repetition; and (3) semantics – word meaning.

Reading is accomplished by the division of labour between the three systems. In particular, a mapping between vision and phonology (V>P) permits reading of regular words with a high speech-sound correspondence (e.g., *mint*) or high frequency irregular words (e.g., *have*), whereas irregular words with a less regular speech-sound correspondence (e.g., *colonel*, *pint*) are supported by the semantic system (V>S>P) (Woollams, 2013).

Figure 2 about here

Despite evidence confirming this alternative view in accommodating the impairments in some of the acquired dyslexias (e.g., visual impairments in pure alexia, semantic impairments in surface dyslexia, and phonological impairments in phonological dyslexia), there is insufficient evidence to establish the capacity of this model to also explain impairments in DD (Woollams, 2013). A prediction that follows from this model is that individuals with DD, when tested appropriately, will show deficits in non-reading tasks, depending on which primary system is damaged. For instance, a degraded incoming visual signal caused by a narrow attentional window will affect reading and other visual tasks that demand similar processing (Gabay et al., 2017). Moreover, due to the interactive nature of the model, it is also predicted that a dysfunctional visual system may affect performance of other types of task that necessitate visual processing such as visuo-spatial working memory.

Working memory (WM) is a limited capacity system, which enables the temporary storage and maintenance of information (Baddeley & Hitch, 1974; see Cornoldi & Giofrè, 2014 for a review). Several WM models are available but the classical tripartite model, which distinguishes between two slave systems (verbal and visuo-spatial) and a central executive component, has received substantial support in the literature (Baddeley, 1986; Cornoldi & Giofrè, 2014). Deficits in the verbal component seem to be quite severe and a core feature of performance in DD (e.g., Peng & Fuchs, 2016; Toffalini, Giofrè, & Cornoldi, 2017). Hence, previous studies have focused on the verbal domain (e.g., Majerus & Cowan, 2016), with the visuo-spatial component receiving little attention (with some exceptions see Cowan et al., 2017; Smith-Spark & Fisk, 2007; Smith-Spark, Fisk, Fawcett, & Nicolson, 2003). It therefore remains to be determined whether, as with acquired disorders of reading, visuo-spatial working memory (VSWM) impairments can explain an additional portion of the variance in word reading in DD after controlling for verbal WM skills.

According to the primary system hypothesis, a number of predictions can be made. First, individuals with DD should also present with visual deficits, as evidenced in patients with acquired dyslexia (i.e., pure alexia, see Roberts et al., 2013, 2015). To test this prediction, we used visual discrimination tasks with unfamiliar objects – checkerboards and Kanji characters (see Methods section and Figures 4 and 5 for detailed information of these tasks). We chose to use non-orthographic stimuli to assess visual processing *per se* and to avoid underestimating the severity of the visual impairment. For instance, using familiar stimuli might result in top-down semantic support which may compensate for, or boost activation of, an impaired visual system (Plaut, 1999). Moreover, studies conducted on DD children in Japan, a logographic orthography in which the orthographic units are pictograms (i.e., Kanji), showed that these children exhibited difficulties in reading and writing Kanji (e.g., Kaneko, Uno, Kaga, Inagaki, & Haruhara, 1997; Uno, Kaga, & Inagaki, 1995). The authors argued that such difficulties might be explained by problems in visual or visuo-spatial processing. Indeed, the role of phonology is less prominent in orthographies in which the units employed to read are coarser than the single grapheme (i.e., pictograms, see Wydell & Butterworth, 1999). Thus, the difficulties shown by individuals with DD in those orthographies might be underpinned by a compromised visual system. What we aim to investigate in this study is the extent to which an impairment in visual processing may also characterize DD reading of alphabetic orthographies.

Second, impairments in WM are not only limited to the verbal domain but can also affect the visuo-spatial aspects, in particular those that place maximal demands on attentional control. For this reason, we used VSWM tasks that were demanding in terms of attentional control (see Methods section and Figure 3). We expected that a) a low-level impairment in visual processing will affect the performance of individuals with DD in VSWM tasks and b) poor performance will be exaggerated in tasks that require more attentional control.

Third, DD should be considered as a complex disorder encompassing general processing deficits in both phonological and visual domains. Hence, phonology was measured in accordance with the predominant literature indicating deficits in this skill in individuals with DD. Finally, DD could be also characterized by a low-level auditory deficit. Indeed, some research has shown that impaired processing of brief sounds might be detrimental to speech perception, thus aggravating the phonological deficit (e.g., Molinaro et al., 2016; Wright et al., 1997).

Method

Participants

Eighteen university students with DD (5 males; age range 19-27; M_{age} = 21.8; SD = 2.29) participated. All were native speakers of English and in receipt of a formal diagnosis of dyslexia (supplied by a registered assessor of SpLD), as required for access arrangements and additional support in UK higher education institutions. Participants with DD have been contrasted to a typically developing readers (TDR) group comprising 18 students (7 males; age range 19-28; M_{age} = 21.8; SD = 2). The two groups did not differ statistically for gender, $\chi^2(1) = 0.50$, $p = .480$, Cramer's $V = .118$, or age, $F(1, 34) = 0.02$, $p = .878$, $\eta^2_p = .001$.

The reading level of the two groups was assessed using two reading tasks (word and non-word reading, see Roberts, Lambon Ralph, & Woollams, 2010). As expected, participants in the two groups differed statistically with DD performing worse than TDR when reading words, $F(1, 34) = 6.86$, $p = .013$, $\eta^2_p = .168$, and non-words, $F(1, 34) = 7.68$, $p = .009$, $\eta^2_p = .184$. To tap general cognitive abilities, we employed a multimodal vocabulary naming test (Hoffman & Lambon Ralph, 2013; Mackenzie-Phelan & Roberts, 2018). The two

groups did not differ on this measure of general cognitive ability (i.e., multimodal

vocabulary), $F(1, 34) = 2.55$, $p = .119$, $\eta^2_p = .070$.

Materials

      Visuo-spatial working memory tasks (Mammarella, Caviola, Giofrè, & Szűcs,

2018). Three VSWM tasks were employed in this study: balloons, sequential matrices and

simultaneous matrices. Two trials for each span were presented. Partial credit score was used

for scoring purposes. This scoring procedure allows for a more precise estimation of the WM

capacity of each individual by considering the partial recall. For example, if a participant

correctly recalled 5 out 6 stimuli in the correct order in one trial the score for that trial would

be 5 (see Giofrè & Mammarella, 2014; Unsworth & Engle, 2006, 2007 for the statistical

rationale). It is worth noting that the current literature disincentive the use of proportion of

correct responses or percentages, because they often alter the raw and are somehow more

imprecise (e.g., Unsworth & Engle, 2007). For balloons and simultaneous matrices, stimuli

were simultaneously presented, therefore the order of recalling was irrelevant for this task.

For the sequential matrices span, participants were required to recall the items in the right

order of presentation. In this latter task, partial recall was constituted by the sum of the

stimuli correctly recalled in the correct order of presentation.

      For the balloons task, the stimuli were schematic drawings seen from the front.

Initially, a set of two drawings is shown for 4 seconds (Figure 1). Immediately after

presentation, the participant has to recognize the target drawings (by clicking on it) within a

set comprising three stimuli. Then a set of three drawings was presented for the same length

of time and the participant must recognize them among a total of five drawings. From there,

three larger sets of drawings were also used. The set of four, five, and six target drawings

were placed in groups of six, eight and nine drawings, respectively (min possible score = 0 and max possible score = 40).

In the sequential matrices task, participants were asked to memorize and recall the positions of black cells that appeared for 1 second in different positions on a 5×5 grid. After a series of black cells had been presented, participants clicked on the locations where they had seen a black cell appear in the right order. The number of black cells presented in each series ranged from 2 to 8 (min possible score = 0 and max possible score = 72).

In the simultaneous matrices task, participants had to memorize and recall the position of a number of black dots, which appeared simultaneously for 3 seconds on a 5×5 grid. All of these tasks were of increasing difficulty. Participants were presented for 1.5s with a 5×5 grid. The number of black dots presented in each grid ranged from 2 to 8. After 3s the initial stimulus was removed and participants were presented with a blank test matrix in which they had to click on the previously filled squares. The number of black cells presented in each series ranged from 2 to 8 (min possible score = 0 and max possible score = 72).

Figure 3 about here

Visual matching tasks (Roberts et al., 2013). Two visual matching tasks were employed to assess visual abilities and are described below. For each of these tasks, RT and accuracy data were collected.

Checkerboards. A set of 32 black and white checkerboards were used. The number of squares in each matrix was either 9 (3×3) or 49 (7×7), forming the visually simple and visually complex sets respectively. Grids were constructed by avoiding placement of blocks of the same colour together or any other regularity in the patterns (that might simplify visual processing). Stimuli were used to form a triad-based matching-to-sample task, in which the

probe was flanked above and below by the target and foil. The position (above/below) of

target and foil was randomized. Three vertically aligned checkerboards appeared on the

screen for each trial. The central checkerboard was the probe stimulus, and the participants

had to decide whether the top or bottom checkerboard matched the central one (i.e., they had

to identify the target), by pressing two different keys on the keyboard ("N" for the stimulus

below and "Y" for the stimulus below). Each participant was required to respond as quickly

and accurately as possible.

   Kanji Characters. A set of 60 single Kanji characters were used. Visual complexity

was defined in terms of the number of strokes in each character. Characters with 2-4 strokes

constituted the simple items, and those with 13 strokes formed the complex set. Again, each

target character appeared in a matching-to-sample triad. The probe was placed in the centre

with the target and foil above or below. The position of the target was randomized across

trials. Three vertically aligned Kanji appeared on the screen for each trial. The central Kanji

was the probe stimulus, and the participants had to decide whether the top or bottom Kanji

matched the central one (i.e., they had to identify the target), by pressing two different keys

on the keyboard ("N" for the stimulus below and "Y" for the stimulus below). Each

participant was required to respond as quickly and accurately as possible.

                Figure 4 and 5 about here

   Phonological tasks (WAIS-IV, Wechsler, 2008). To investigate phonological

processing the digit span test was used. This test consists of three subtasks: digit forward, in

which participants were instructed to recall as many of the digits as possible in the same order

they were presented; digit backward, in which participants had to recall the digits in the

reverse order; and digit sequential, which required participants to recall the digits in

ascending order of magnitude. The span test score is obtained by summing up the scores in

the three span conditions (see Wechsler, 2008 for more detailed information).

Auditory matching tasks (Roberts, 2010). An identical design to the checkerboard

and Kanji task was employed. To control for the presence of an impairment in auditory

processing, an auditory matching task was employed to assess auditory abilities. This tests

purely auditory processing (stripped of meaning, lexical properties etc.). Three tones were

presented for each trial. The last tone was the probe stimulus, and the participants had to

decide whether the first or the second tone matched the last one (i.e., they had to identify the

target), by pressing two different keys on the keyboard ("1" for first stimulus presented and

"2" for the second stimulus presented). Each participant was required to respond as quickly

and accurately as possible. RT and accuracy data were collected for the task.

Procedure

All tasks were administered using E-Prime 2.0 software (MacWhinney, St. James,

Schunn, Li, & Schneider, 2001). Students were assessed individually in a single session

lasting approximately 1 hour in a quiet room at Liverpool John Moores University. The study

was approved by the RES Committee North West – Liverpool Central (15/NW/0461) and

written consent was obtained from all participants.

Results

Means and standard deviations for both RTs and accuracy of the two groups are

displayed in Table 1.

Table 1 about here

Data analyses

SPSS (Version 25; IBM, 2017) was used to perform all analyses. Before conducting the discriminant function analysis, issues related to sample size and multivariate normality were addressed (Tabachnick & Fidell, 1996). The criterion that the sample size of the smallest group should exceed the number of predictors was met. Group size was equal, ensuring multivariate normality.

ANOVAs and MANOVAs

VSWM tasks. A MANOVA was performed comparing VSWM tasks (balloons, sequential matrices, simultaneous matrices) in the two groups (Figure 6). A significant effect of the group, $F(3, 32) = 6.62$, $p = .001$, $\eta^2_p = .383$, was found, with a large effect size. Participants with DD performed significantly worse than TDR in all the VSWM tasks, with effect sizes ranging from moderate to large. Follow up ANOVAs are presented in Table 1.

Figure 6 about here

Visual processing. A MANOVA was performed comparing RTs in the visual tasks (checkerboards and Kanji – Figure 7). A significant effect of Group, $F(2, 33) = 3.63$, $p = .037$, $\eta^2_p = .181$, with a medium effect size was identified. Participants with DD performed worse than the TDR group in both tasks, with moderate effect sizes. A MANOVA was also performed for the accuracy in these tasks. The results showed no significant differences between the DD group and TDR group, $F(2, 33) = 1.11$, $p = .340$, $\eta^2_p = .063$, with a small effect size. Follow up ANOVAs are presented in Table 1.

Means and standard deviations for the four conditions in checkboards and Kanji tasks (i.e., high complexity low similarity, high complexity high similarity, low complexity high similarity and low complexity low similarity) are presented in Table 2.

Table 2 about here

Figure 7 about here

Phonological processing. We performed an ANOVA to compare the performances of the two groups (Figure 8). The results showed that the DD group performed worse than TDR group, $F(1, 34) = 25.18$, $p < .001$, $\eta^2_p = .426$, with a large effect size.

Figure 8 about here

Auditory processing. We performed an ANOVA to compare the performances of the two groups in both RTs (Figure 9) and accuracy (Figure 10). With respect to the RTs, the results showed that the DD group performed worse than TDR group, $F(1, 34) = 5.15$, $p < .030$, $\eta^2_p = .131$ with a medium effect size. The DD group performed worse than TDR group also in accuracy, $F(1, 34) = 11.66$, $p = 002$, $\eta^2_p = .255$, with a large effect size.

Figure 9 and 10 about here

Discriminant function analysis

Discriminant analysis is generally used to determine which variables discriminate between two or more groups. Discriminant analysis is also used to investigate how variables contribute to group separation, and to what degree. Here, discriminant function analysis was performed to establish which tasks had the greatest discriminatory power to distinguish between participants with DD and TDR. The criterion that the sample size of the smallest group should exceed the number of predictors was met, and the group size was equal, ensuring multivariate normality. The discriminant analysis was conducted with the stepwise method, using all the tasks of the VSWM, visual, verbal and auditory domains. Only a visual matching task (i.e., the Kanji task) and a verbal working memory task (i.e., the span test) were included in the model, with a Wilk's $\lambda = .47$, which indicates that these two predictors were the best variables to discriminate between the two groups.

The discriminant function analysis showed a reliable association with both the DD and the TDR group, $\chi^2(2) = 25.03$, p $<.001$. The Kanji task and the span test were able to correctly discriminate 100% of the TDR group (i.e., 18/18) and 83.3% of the DD group (i.e., 15/18). Overall, the model was able to discriminate 91.7% of the participants. This finding indicates that these two tasks, i.e., Kanji and span test, had the greater discriminatory power as compared to all the other tasks included in this study. Thus, performance on tasks from both the phonological and the visual domain is required to discriminate participants with DD from those who have made typical progress in reading.

Discussion

The aim of this study was to investigate whether individuals with DD present with linguistic impairments only, which are well captured by the DRC model, or if they also present with impairments in the visual domain in addition to phonological impairments, a position that aligns more closely with the triangle model. We aimed to describe such impairments within the framework of the triangle model, an instantiation of the primary system hypothesis. In order to achieve these aims a group of individuals with DD was compared with a matched group of TDRs using a comprehensive cognitive battery, including a number of visual, phonological, and auditory tasks.

The results demonstrated a phonological impairment in the DD group, who performed significantly worse on the span test, with a large effect size. This finding confirms previous evidence highlighting impaired performance compared to controls on phonological tasks (Carroll & Snowling, 2004; Paulesu, 2001; Snowling, 1981). More critically, the DD group also performed worse on VSWM and visual processing tasks. These results indicate that in addition to phonologically-based deficits, individuals with DD also have difficulties in processing visual and visuo-spatial information. This has important theoretical implications, since although it is well established that individuals with DD have difficulties in verbal WM tasks (e.g., Ackerman & Dykman, 1993; Gathercole et al., 2016), evidence of a visual processing deficit, and VSWM in particular, are scarcely investigated (with some exceptions e.g., Menghini, Finzi, Carlesimo, & Vicari, 2011).

Although the group with DD were impaired on all VSWM tasks, they were disproportionately impaired on one particular task – the sequential matrices. In fact, some visuo-spatial WM models, including for example Cornoldi and Vecchi (2003) and Kane and co-authors (2004) distinguished between tasks requiring different degrees of attentional control. This might explain at least in part why individuals with DD tend to be more impaired

in tasks requiring sequential recall (e.g., sequential matrices and digit span), which place maximal demands on attentional control (Cornoldi & Vecchi, 2003). Notably, difficulty with sequential tasks, either verbal or visuo-spatial, also occurs in individuals with other learning difficulties, such as dyscalculia or non-verbal learning disabilities (Bizzaro, Giofrè, Girelli, & Cornoldi, 2018; Mammarella, Caviola, Giofrè, & Szűcs, 2018; Mammarella, Giofrè, Ferrara, & Cornoldi, 2013). This supports the view that individuals with DD might struggle with sequential tasks (Helland & Asbj⊘rnsen, 2003; Plaza & Guitton, 1997).

As for the non-orthographic visual tasks, with a minimal requirement of WM abilities, the DD group also showed an impairment, particularly in speed of responding. These findings are similar to those obtained with acquired dyslexic patients (Roberts et al., 2013) and are consistent with explanations of a visual deficit contributing to DD. It is worth noting that visual deficits were captured in speed of processing rather than accuracy, and such impairments could easily be missed if only accuracy is measured. Hence, it is important to measure response speed when visual processing is evaluated in DD and in this scenario visual impairments might be more prominent in DD. These findings, along with those obtained in the VSWM tasks, support the claim that a deficit in visual processing may characterize some individuals with DD.

Our study also aimed to investigate whether visual and phonological processing tasks could discriminate between DD and TDR group membership. The discriminant function analysis demonstrated that the digit span and the Kanji tasks were best able to discriminate between the two groups. The fact that both visual and phonological tasks were required for successful discrimination supports a position of both phonological and visual processing skills being important in the dyslexic profile. These findings represent an aspect of novelty and are better accommodated by the triangle model. Indeed, the triangle model is a domain general model explaining reading difficulties in terms of a deficit to a tripartite of basic

underlying systems (vision, phonology, and semantics). On this account, DD may occur as a consequence of damage to the phonological and visual systems, which produces difficulties in reading along with deficits in phonological or visual processing.

Taking up this point, individuals with DD performed significantly worse than TDR on the tone test in both accuracy and RTs, with large effect sizes. These findings confirmed those of previous research and indicate the presence of some low-level sensory deficit (Goswami, 2015; Goswami et al., 2002; Marshall, Snowling, & Bailey, 2001). However, auditory tasks do not discriminate between the two groups when the other variables are entered into the equation. This might emphasise that, even though presenting with some low-level sensory deficit, phonological impairments explain a larger proportion of variance. Indeed, when the phonological tasks are entered into the model, they showed better discriminatory power in distinguishing between DD and TDR groups than the auditory task. Such a result, stresses the importance of phonology and not merely auditory processing in adults with DD. Furthermore, it would be interesting to evaluate processing skills in the phonological and visual domains of dyslexic readers within different cultures, particularly those reading different orthographies (e.g., transparent languages such as Italian, see Provazza, Giofrè, Adams, & Roberts, 2019 for some considerations about dyslexia in different languages). Finally, large scale studies should be performed to understand whether dyslexia operates as an umbrella term encompassing several different problems, such as phonological and visual processing (Giofrè et al., 2019).

This study highlights some interesting future research directions. The visual tasks included in this study might require both visual decoding and visual perceptual processing. We are of the view that the visual deficit and visual attention deficit may be overlapping – they both recruit activations of ventral and dorsal visual pathways, but they are, at least in part, distinguishable. Visual tasks in the present study might be more related to some basic

visual decoding skills rather than to visual attention span. Further research is needed to disentangle between these two processes, which might reflect different underlying mechanisms. The phonological test used in this task might, in some way, reflect verbal short-term-memory capacities. In fact, it can be argued that the auditory matching tasks also involved short-term memory considering that the presentation is serial as compared to the simultaneous presentation of stimuli in visual matching tasks.

Furthermore, the VSWM tests might also be related with visual short-term memory, verbal short-term memory, and some basic visual decoding. For instance, some tasks seemed not so related to visuospatial attention but exhibited some relationship with memory. This could be accounted for example, by the working memory triarchic model postulated by Baddeley and Hitch (1974), which contains both visual spatial processing and the verbal circle. This is also accommodated by other WM models such as those considering attention as a fundamental part of working memory capacity (see for example Engle, 2010 for an historical perspective). The authors recognize that it is often very hard to distinguish between attention and WM, since very simple tasks might require memory resources whilst at the same time complex span tasks always require higher levels of cognitive control and higher attentional resources (see Engle, 2010 on this point). Despite these limits, the evidence here raises questions about the range of possible causes of DD, including the often overlooked visual processing deficit.

This research presents with several aspects of novelty compared to previous research. If the generalised visual impairment hypothesis for DD is correct, then a number of key questions emerge including: (1) what is the critical nature of the visual impairment and (2) why are written words so vulnerable to this impairment? Answering these questions will necessitate further research using a larger sample but the present study indicates that individuals with DD may be impaired on visual, phonological, and visuo-spatial tasks. For

this reason, we can speculate that individuals with DD may present with a deficit in the visual as well as in the phonological domain, and that their difficulties in reading may arise as the consequence of these several deficits. As expected, not all individuals with DD showed the same pattern of impairment compared to the TDR group (see Supplementary Materials). These findings confirm that DD is a complex disorder characterized by deficits in different cognitive mechanisms (visual and phonological) that underpin reading. Practitioners working in this field should thus consider assessing a diverse range of abilities rather than limiting their focus to phonological skills, to fully capture the difficulties children may encounter when learning to read.

References

Ackerman, P. T., & Dykman, R. A. (1993). Phonological Processes, Confrontational Naming, and Immediate Memory in Dyslexia. *Journal of Learning Disabilities*, *26*(9), 597–609. https://doi.org/10.1177/002221949302600910

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders (5th ed.).* Washington, DC: Author.

Ans, B., Carbonnel, S., & Valdois, S. (1998). A connectionist multiple-trace memory model for polysyllabic word reading. *Psychological Review*, *105*(4), 678–723. https://doi.org/10.1037/0033-295X.105.4.678-723

Baddeley, A. D. (1986). *Working memory (vol. 11).* Oxford, England: Oxford University Press.

Baddeley, A. D., & Hitch, G. J. (1974). Working Memory. In G. A. Bower (Ed.), *The Psychology of Learning and Motivation: Advances in Research and Theory* (Vol. 8, pp. 47–90). New York: Academic Press.

Bizzaro, M., Giofrè, D., Girelli, L., & Cornoldi, C. (2018). Arithmetic, working memory, and visuospatial imagery abilities in children with poor geometric learning. *Learning and Individual Differences*, *62*, 79–88. https://doi.org/10.1016/j.lindif.2018.01.013

Boden, C., & Giaschi, D. (2007). M-stream deficits and reading-related visual processes in developmental dyslexia. *Psychological Bulletin*, *133*(2), 346–366. https://doi.org/10.1037/0033-2909.133.2.346

Bosse, M.-L., Tainturier, M. J., & Valdois, S. (2007). Developmental dyslexia: The visual attention span deficit hypothesis. *Cognition*, *104*(2), 198–230. https://doi.org/10.1016/j.cognition.2006.05.009

Bruck, M. (1992). Persistence of dyslexics' phonological awareness deficits. *Developmental Psychology*, *28*(5), 874–886. https://doi.org/10.1037/0012-1649.28.5.874

Carroll, J. M., & Snowling, M. J. (2004). Language and phonological skills in children at

    high risk of reading difficulties. *Journal of Child Psychology and Psychiatry*, *45*(3),

    631–640. https://doi.org/10.1111/j.1469-7610.2004.00252.x

Castles, A. (1996). Cognitive Correlates of Developmental Surface Dyslexia: A Single Case

    Study. *Cognitive Neuropsychology*, *13*(1), 25–50.

    https://doi.org/10.1080/026432996382051

Castles, A., Bates, T., & Coltheart, M. (2006). John Marshall and the developmental

    dyslexias. *Aphasiology*, *20*(9), 871–892. https://doi.org/10.1080/02687030600738952

Castles, A., & Coltheart, M. (1993). Varieties of developmental dyslexia. *Cognition*, *47*(2),

    149–180. https://doi.org/10.1016/0010-0277(93)90003-E

Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). DRC: A dual route

    cascaded model of visual word recognition and reading aloud. *Psychological Review*,

    108(1), 204–256. https://doi.org/10.1037/0033-295X.108.1.204

Cornoldi, C., & Giofrè, D. (2014). The crucial role of working memory in intellectual

    functioning. *European Psychologist*, *19*(4), 260–268. https://doi.org/10.1027/1016-

    9040/a000183

Cornoldi, C., & Vecchi, T. (2003). *Visuo-spatial working memory and individual differences*.

    Hove: Psychology Pr.

Cowan, N., Hogan, T. P., Alt, M., Green, S., Cabbage, K. L., Brinkley, S., & Gray, S. (2017).

    Short-term memory in childhood dyslexia: Deficient serial order in multiple modalities.

    Dyslexia, *23*(3), 209–233. https://doi.org/10.1002/dys.1557

Fraser, J., Goswami, U., & Conti-Ramsden, G. (2010). Dyslexia and specific language

    impairment: The role of phonology and auditory processing. *Scientific Studies of

    Reading*, *14*(1), 8–29. https://doi.org/10.1080/10888430903242068

Frey, A., & Bosse, M.-L. (2018). Perceptual span, visual span, and visual attention span:

Three potential ways to quantify limits on visual processing during reading. *Visual Cognition*, *26*(6), 412–429. https://doi.org/10.1080/13506285.2018.1472163

Friedmann, N., & Coltheart, M. (2016). Types of developmental dyslexia. In A. Bar-On & D. Ravid (Eds.), *Handbook of communication disorders: Theoretical, empirical, and applied linguistics perspectives*. Berlin, Boston.

Gabay, Y., Dundas, E., Plaut, D., & Behrmann, M. (2017). Atypical perceptual processing of faces in developmental dyslexia. *Brain and Language*, *173*, 41–51. https://doi.org/10.1016/j.bandl.2017.06.004

Gathercole, S. E., Woolgar, F., Kievit, R. A., Astle, D., Manly, T., & Holmes, J. (2016). How Common are WM Deficits in Children with Difficulties in Reading and Mathematics? *Journal of Applied Research in Memory and Cognition*, *5*(4), 384–394. https://doi.org/10.1016/j.jarmac.2016.07.013

Giofrè, D., Toffalini, E., Provazza, S., Calcagni, A., Altoè, G., & Roberts, D. J. (2019). Are children with developmental dyslexia all the same? A cluster analysis with more than 300 cases. *Manuscript Submitted for Publication*.

Goswami, U. (2015). Sensory theories of developmental dyslexia: Three challenges for research. *Nature Reviews Neuroscience*, *16*(1), 43–54. https://doi.org/10.1038/nrn3836

Goswami, U., Thomson, J., Richardson, U., Stainthorp, R., Hughes, D., Rosen, S., & Scott, S. K. (2002). Amplitude envelope onsets and developmental dyslexia: A new hypothesis. *Proceedings of the National Academy of Sciences*, *99*(16), 10911–10916. https://doi.org/10.1073/pnas.122368599

Heiervang, E., Stevenson, J., & Hugdahl, K. (2002). Auditory processing in children with dyslexia. *Journal of Child Psychology and Psychiatry*, *43*(7), 931–938. https://doi.org/10.1111/1469-7610.00097

Helland, T., & Asbj⊘rnsen, A. (2003). Visual-sequential and visuo-spatial skills in dyslexia:

Variations according to language comprehension and mathematics skills. *Child Neuropsychology*, *9*(3), 208–220. https://doi.org/10.1076/chin.9.3.208.16456

Hoffman, P. and M. A. Lambon Ralph (2013). Shapes, scents and sounds: quantifying the full multi-sensory basis of conceptual knowledge. Neuropsychologia 51(1): 14-25.

Hoffman, P., Lambon Ralph, M. A., & Woollams, A. M. (2015). Triangulation of the neurocomputational architecture underpinning reading aloud. *Proceedings of the National Academy of Sciences*, *112*(28), E3719–E3728. https://doi.org/10.1073/pnas.1502032112

Job, R., Sartori, G., Masterson, J., & Coltheart, M. (1984). Developmental Surface Dyslexia in Italian. In *Dyslexia: A Global Issue* (pp. 133–141). Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-94-009-6929-2_7

Jones, M. W., Branigan, H. P., & Kelly, M. L. (2008). Visual deficits in developmental dyslexia: relationships between non-linguistic visual tasks and their contribution to components of reading. *Dyslexia*, *14*(2), 95–115. https://doi.org/10.1002/dys.345

Kane, M. J., Hambrick, D. Z., Tuholski, S. W., Wilhelm, O., Payne, T. W., & Engle, R. W. (2004). The generality of working memory capacity: a latent-variable approach to verbal and visuospatial memory span and reasoning. *Journal of Experimental Psychology: General*, *133*(2), 189–217. https://doi.org/10.1037/0096-3445.133.2.189

Lallier, M., & Valdois, S. (2012). Sequential versus simultaneous processing deficits in developmental dyslexia. *Dyslexia-A Comprehensive and International Approach. InTech*.

Lobier, M., Zoubrinetzky, R., & Valdois, S. (2012). The visual attention span deficit in dyslexia is visual and not verbal. *Cortex*, *48*(6), 768–773. https://doi.org/10.1016/j.cortex.2011.09.003

Mackenzie-Phelan, R. and Roberts, D. (2018). Multimodal conceptual knowledge influences

lexical retrieval speed: evidence from object-naming and word-reading in healthy adults. Frontiers in Human Neuroscience, 12. ISSN: 1662-5161

MacWhinney, B., St. James, J., Schunn, C., Li, P., & Schneider, W. (2001). STEP—A System for teaching experimental psychology using E-Prime. *Behavior Research Methods, Instruments, & Computers*, *33*(2), 287–296. https://doi.org/10.3758/BF03195379

Majerus, S., & Cowan, N. (2016). The nature of verbal short-term impairment in dyslexia: The importance of serial order. *Frontiers in Psychology*, *7*. https://doi.org/10.3389/fpsyg.2016.01522

Mammarella, I. C., Caviola, S., Giofrè, D., & Szűcs, D. (2018). The underlying structure of visuospatial working memory in children with mathematical learning disability. *British Journal of Developmental Psychology*, *36*(2), 220–235. https://doi.org/10.1111/bjdp.12202

Mammarella, I. C., Giofrè, D., Ferrara, R., & Cornoldi, C. (2013). Intuitive geometry and visuospatial working memory in children showing symptoms of nonverbal learning disabilities. *Child Neuropsychology*, *19*(3), 235–249. https://doi.org/10.1080/09297049.2011.640931

Marshall, C. M., Snowling, M. J., & Bailey, P. J. (2001). Rapid Auditory Processing and Phonological Ability in Normal Readers and Readers With Dyslexia. *Journal of Speech, Language, and Hearing Research*, *44*(4), 925–940. https://doi.org/10.1044/1092-4388(2001/073)

Martin, F., & Lovegrove, W. (1984). The effects of field size and luminance on contrast sensitivity differences between specifically reading disabled and normal children. *Neuropsychologia*, *22*(1), 73–77. https://doi.org/10.1016/0028-3932(84)90009-5

Menghini, D., Finzi, A., Carlesimo, G. A., & Vicari, S. (2011). Working Memory Impairment

in Children With Developmental Dyslexia: Is it Just a Phonological Deficity? *Developmental Neuropsychology*, *36*(2), 199–213. https://doi.org/10.1080/87565641.2010.549868

Molinaro, N., Lizarazu, M., Lallier, M., Bourguignon, M., & Carreiras, M. (2016). Out-of-synchrony speech entrainment in developmental dyslexia. *Human Brain Mapping*, *37*(8), 2767–2783. https://doi.org/10.1002/hbm.23206

Patterson, K., & Lambon Ralph, M. A. (1999). Selective disorders of reading? *Current Opinion in Neurobiology*, *9*(2), 235–239. https://doi.org/10.1016/S0959-4388(99)80033-6

Paulesu, E. (2001). Dyslexia: Cultural Diversity and Biological Unity. *Science*, *291*(5511), 2165–2167. https://doi.org/10.1126/science.1057179

Peng, P., & Fuchs, D. (2016). A meta-analysis of working memory deficits in children with learning difficulties. *Journal of Learning Disabilities*, *49*(1), 3–20. https://doi.org/10.1177/0022219414521667

Plaza, M., & Guitton, C. (1997). Working memory limitation, phonological deficit, sequential disorder and syntactic impairment in a child with a severe developmental dyslexia. *Dyslexia*, *3*(2), 93–108. https://doi.org/10.1002/(SICI)1099-0909(199706)3:2<93::AID-DYS79>3.0.CO;2-E

Provazza, S., Giofrè, D., Adams, A.-M., & Roberts, D. J. (2019). The Clock Counts – Length effects in english dyslexic readers. *Frontiers in Psychology*, *10*. https://doi.org/10.3389/fpsyg.2019.02495

Rack, J. P., Snowling, M. J., & Olson, R. K. (1992). The nonword reading deficit in developmental dyslexia: A review. *Reading Research Quarterly*, *27*(1), 28. https://doi.org/10.2307/747832

Ramus, F. (2001). Outstanding questions about phonological processing in dyslexia.

Dyslexia, *7*(4), 197–216. https://doi.org/10.1002/dys.205

Ramus, F. (2003). Theories of developmental dyslexia: Insights from a multiple case study of dyslexic adults. *Brain*, *126*(4), 841–865. https://doi.org/10.1093/brain/awg076

Rey, V., De Martino, S., Espesser, R., & Habib, M. (2002). Temporal processing and phonological impairment in dyslexia: Effect of phoneme lengthening on order judgment of two consonants. *Brain and Language*, *80*(3), 576–591. https://doi.org/10.1006/brln.2001.2618

Roberts, D. J., Lambon Ralph, M. A., & Woollams, A. M. (2010). When does less yield more? The impact of severity upon implicit recognition in pure alexia. *Neuropsychologia*, *48*(9), 2437–2446. https://doi.org/10.1016/j.neuropsychologia.2010.04.002

Roberts, D. J., Woollams, A. M., Kim, E., Beeson, P. M., Rapcsak, S. Z., & Lambon Ralph, M. A. (2013). Efficient visual object and word recognition relies on high spatial frequency coding in the left posterior fusiform gyrus: Evidence from a case-series of patients with ventral occipito-temporal cortex damage. *Cerebral Cortex*, *23*(11), 2568–2580. https://doi.org/10.1093/cercor/bhs224

Roberts, D. J., Lambon Ralph, M. A., Kim, E., Tainturier, M.-J., Beeson, P. M., Rapcsak, S. Z., & Woollams, A. M. (2015). Processing deficits for familiar and novel faces in patients with left posterior fusiform lesions. Cortex, 72, 79–96. https://doi.org/10.1016/j.cortex.2015.02.003

Robotham, R. J., & Starrfelt, R. (2017). Face and Word Recognition Can Be Selectively Affected by Brain Injury or Developmental Disorders. *Frontiers in Psychology*, *8*. https://doi.org/10.3389/fpsyg.2017.01547

Sigurdardottir, H. M., Fridriksdottir, L. E., Gudjonsdottir, S., & Kristjánsson, Á. (2018). Specific problems in visual cognition of dyslexic readers: Face discrimination deficits

predict dyslexia over and above discrimination of scrambled faces and novel objects. *Cognition*, *175*, 157–168. https://doi.org/10.1016/j.cognition.2018.02.017

Sigurdardottir, H. M., Ívarsson, E., Kristinsdóttir, K., & Kristjánsson, Á. (2015). Impaired recognition of faces and objects in dyslexia: Evidence for ventral stream dysfunction? *Neuropsychology*, *29*(5), 739–750. https://doi.org/10.1037/neu0000188

Smith-Spark, J. H., & Fisk, J. E. (2007). Working memory functioning in developmental dyslexia. *Memory*, *15*(1), 34–56. https://doi.org/10.1080/09658210601043384

Smith-Spark, J. H., Fisk, J., Fawcett, A., & Nicolson, R. (2003). Investigating the central executive in adult dyslexics: Evidence from phonological and visuospatial working memory performance. *European Journal of Cognitive Psychology*, *15*(4), 567–587. https://doi.org/10.1080/09541440340000024

Snowling, M. J. (1981). Phonemic deficits in developmental dyslexia. *Psychological Research*, *43*(2), 219–234. https://doi.org/10.1007/BF00309831

Snowling, M. J., & Hulme, C. (1989). A longitudinal case study of developmental phonological dyslexia. *Cognitive Neuropsychology*, *6*(4), 379–401. https://doi.org/10.1080/02643298908253289

Spinelli, D., Angelelli, P., De Luca, M., Di Pace, E., Judica, A., & Zoccolotti, P. (1997). Developmental surface dyslexia is not associated with deficits in the transient visual system. *NeuroReport*, *8*(8), 1807–1812. https://doi.org/10.1097/00001756-199705260-00003

Stefanac, N., Spencer-Smith, M., Brosnan, M., Castles, A., & Bellgrove, M. (2019). Visual processing speed as a marker of immaturity in lexical but not sublexical dyslexia. *Cortex*. https://doi.org/10.1016/j.cortex.2019.08.004

Stein, J. (2018). What is Developmental Dyslexia? *Brain Sciences*, *8*(2), 26. https://doi.org/10.3390/brainsci8020026

Stein, J., & Fowler, S. (1981). Visual dyslexia. *Trends in Neurosciences*, *4*, 77–80. https://doi.org/10.1016/0166-2236(81)90026-6

Stein, J., & Walsh, V. (1997). To see but not to read; the magnocellular theory of dyslexia. *Trends in Neurosciences*, *20*(4), 147–152. https://doi.org/10.1016/S0166-2236(96)01005-3

Swan, D., & Goswami, U. (1997). Phonological awareness deficits in developmental dyslexia and the phonological representations hypothesis. *Journal of Experimental Child Psychology*, *66*(1), 18–41. https://doi.org/10.1006/jecp.1997.2375

Tallal, P. (1980). Auditory temporal perception, phonics, and reading disabilities in children. *Brain and Language*, *9*(2), 182–198. https://doi.org/10.1016/0093-934X(80)90139-X

Temple, C. M., & Marshall, J. C. (1983). A case study of developmental phonological dyslexia. *British Journal of Psychology*, *74*(4), 517–533. https://doi.org/10.1111/j.2044-8295.1983.tb01883.x

Toffalini, E., Giofrè, D., & Cornoldi, C. (2017). Strengths and weaknesses in the intellectual profile of different subtypes of specific learning disorder. *Clinical Psychological Science*, *5*(2), 402–409. https://doi.org/10.1177/2167702616672038

Valdois, S., Bosse, M.-L., Ans, B., Carbonnel, S., Zorman, M., David, D., & Pellat, J. (2003). Phonological and visual processing deficits can dissociate in developmental dyslexia: Evidence from two case studies. *Reading and Writing*, *16*(6), 541–572. https://doi.org/10.1023/A:1025501406971

Valdois, S., Bosse, M.-L., & Tainturier, M.-J. (2004). The cognitive deficits responsible for developmental dyslexia: Review of evidence for a selective visual attentional disorder. *Dyslexia*, *10*(4), 339–363. https://doi.org/10.1002/dys.284

Vellutino, F. R. (2004). Specific reading disability (dyslexia): What have we learned in the past four decades? *Journal of Child Psychology and Psychiatry*, *45*(1), 2–40.

Vidyasagar, T. R., & Pammer, K. (2010). Dyslexia: A deficit in visuo-spatial attention, not in phonological processing. *Trends in Cognitive Sciences*, *14*(2), 57–63. https://doi.org/10.1016/j.tics.2009.12.003

Woollams, A. M. (2013). Connectionist neuropsychology: uncovering ultimate causes of acquired dyslexia. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *369*(1634), 20120398–20120398. https://doi.org/10.1098/rstb.2012.0398

Wright, B. A., Lombardino, L. J., King, W. M., Puranik, C. S., Leonard, C. M., & Merzenich, M. M. (1997). Deficits in auditory temporal and spectral resolution in language-impaired children. *Nature*, *387*(6629), 176–178. https://doi.org/10.1038/387176a0

Zoccolotti, P., De Luca, M., Di Pace, E., Judica, A., Orlandi, M., & Spinelli, D. (1999). Markers of developmental surface dyslexia in a language (Italian) with high grapheme–phoneme correspondence. *Applied Psycholinguistics*, *20*(2). https://doi.org/10.1017/S0142716499002027

Zoubrinetzky, R., Bielle, F., & Valdois, S. (2014). New insights on developmental dyslexia subtypes: Heterogeneity of ixmed reading profiles. *PLoS ONE*, *9*(6), e99337. https://doi.org/10.1371/journal.pone.0099337

Zoubrinetzky, R., Collet, G., Serniclaes, W., Nguyen-Morel, M. A., & Valdois, S. (2016). Relationships between categorical perception of phonemes, phoneme awareness, and visual attention span in developmental dyslexia. *PLoS ONE*, *11*(3). https://doi.org/10.1371/journal.pone.0151015
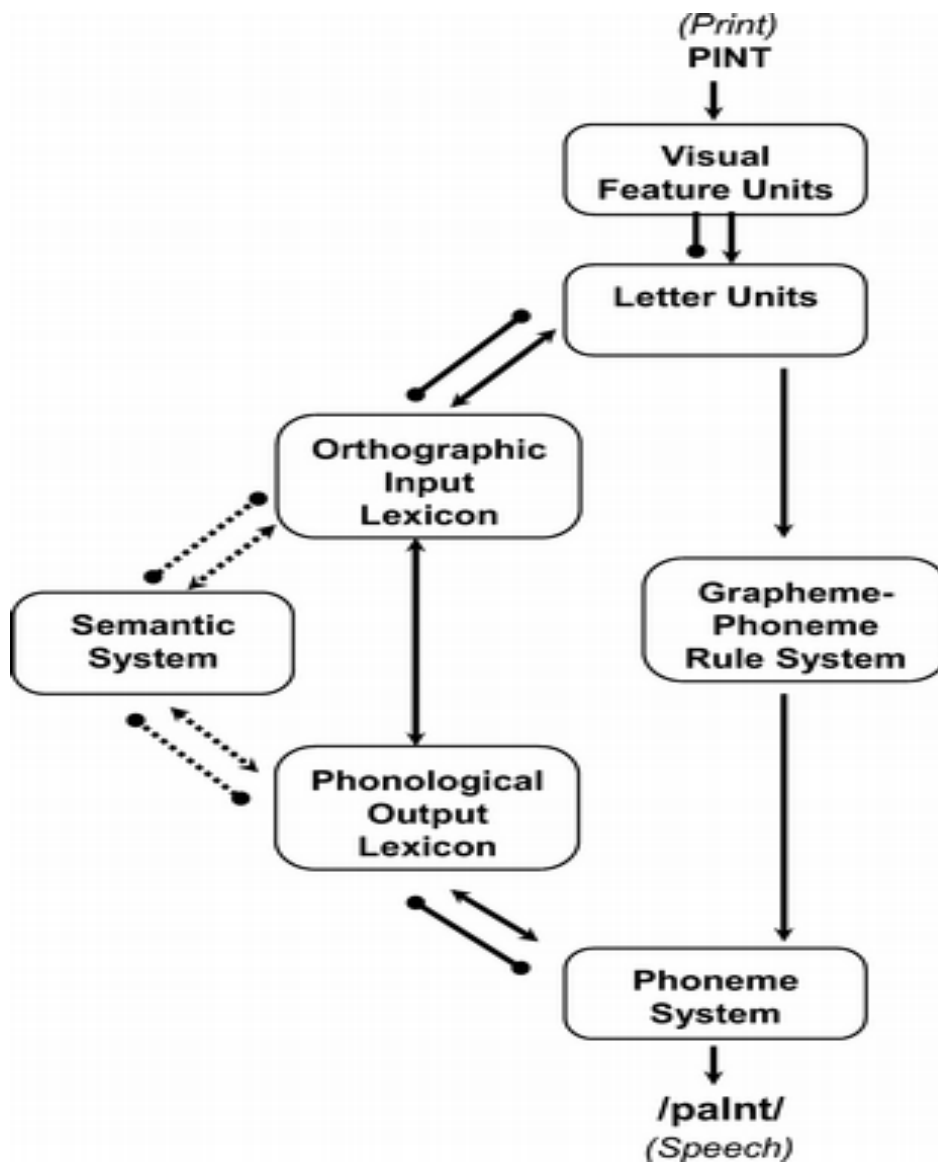
Figure 1. The DRC model (Coltheart et al., 2001).
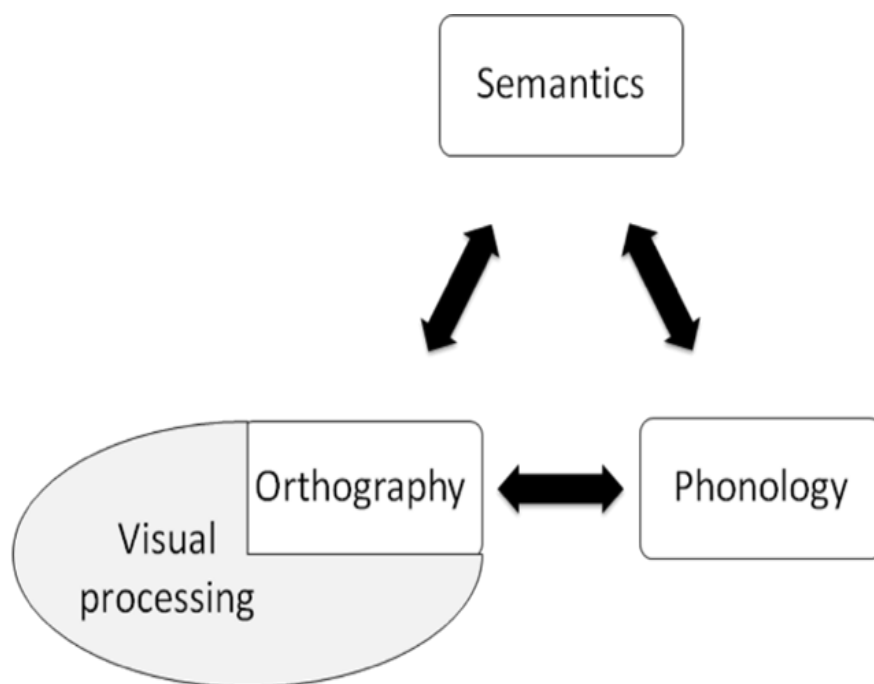
Figure 2. The triangle model (Seidenberg & McClleland, 1989; Plaut, 1996).
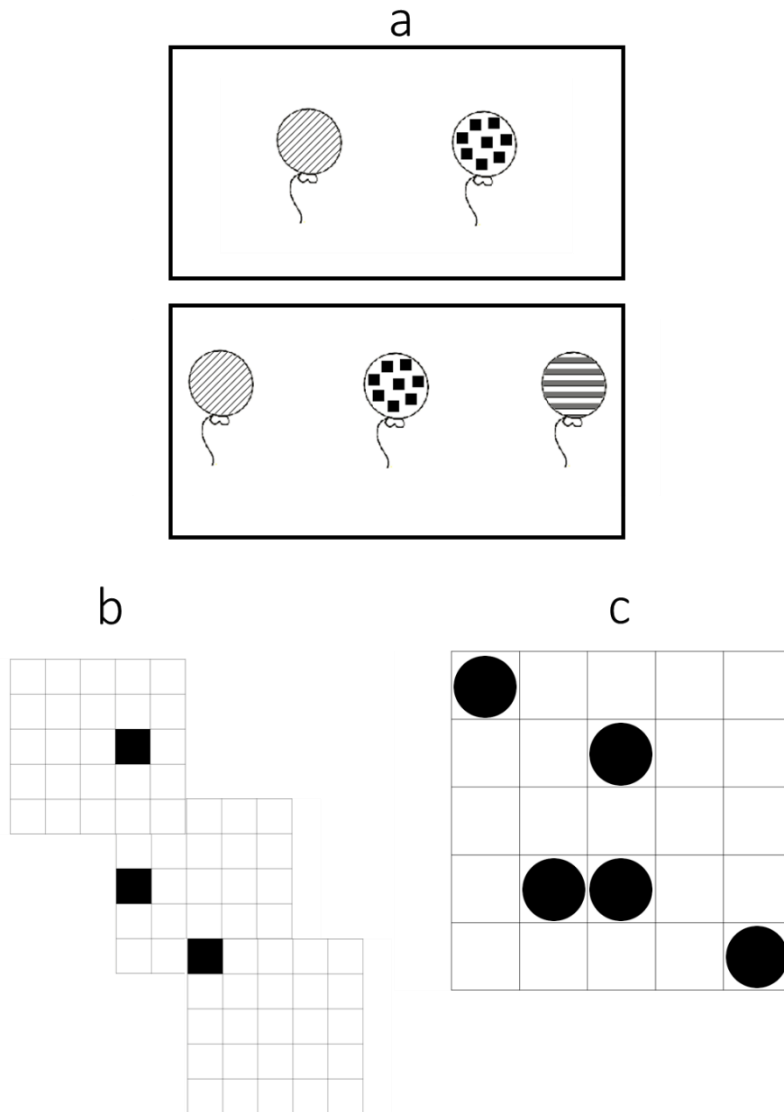
Figure 3. Example VSWM tasks for (a) balloons, (b) sequential matrices, and (c) simultaneous matrices.
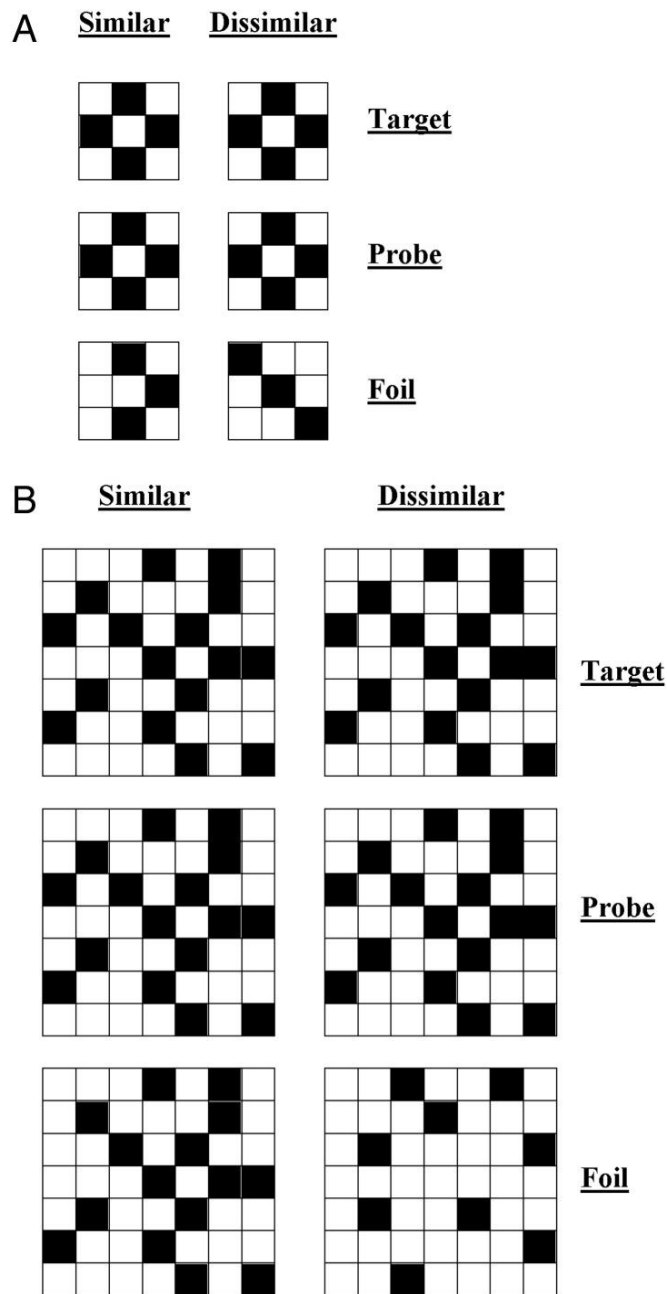
Figure 4. Example checkerboard stimuli for (A) visually simple condition and (B) visually complex condition with similar and dissimilar foils (Roberts et al., 2013).
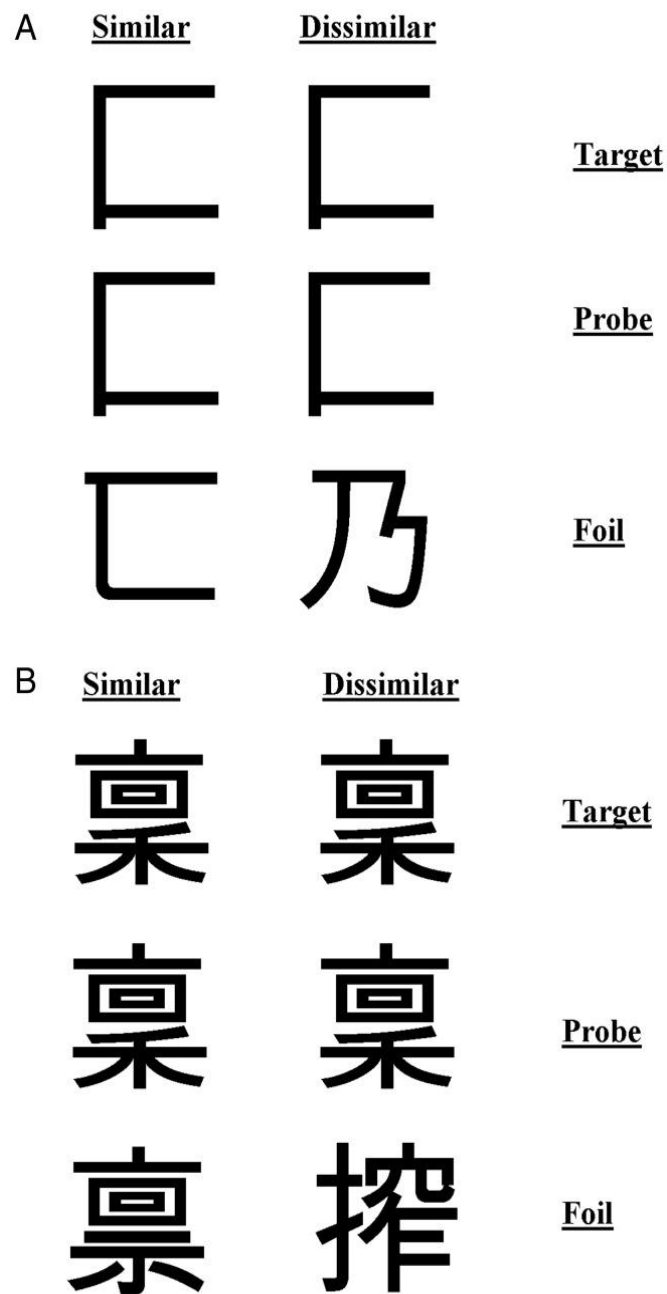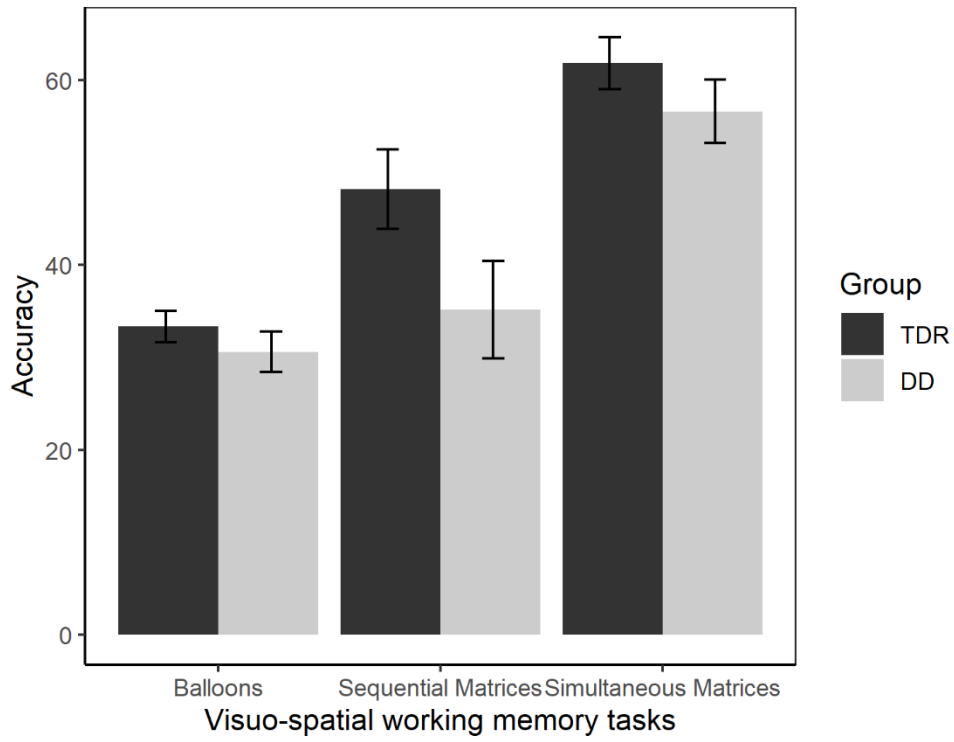
Figure 5. Example Kanji stimuli for (A) visually simple condition and (B) visually complex condition with similar and dissimilar foils (Roberts et al., 2013).

Figure 6. Accuracy on VSWM tasks. Error bars represent standard errors. TDR = typically developing readers, DD = developmental dyslexics.
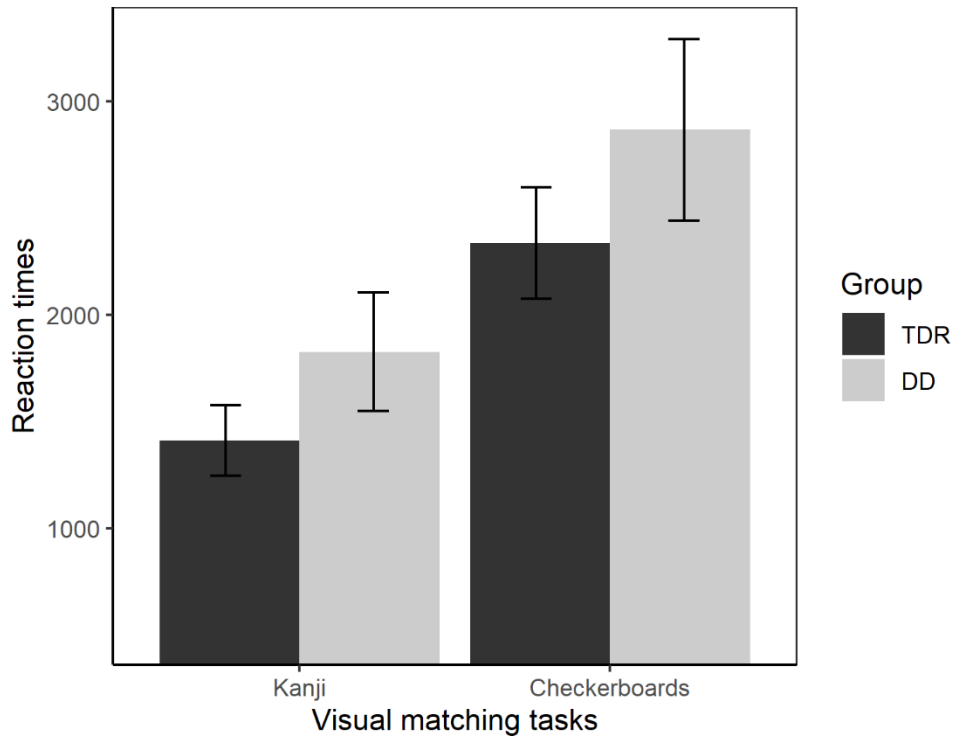
Figure 7. Reaction times on visual tasks. Error bars represent standard errors. TDR = typically developing readers, DD = developmental dyslexics.
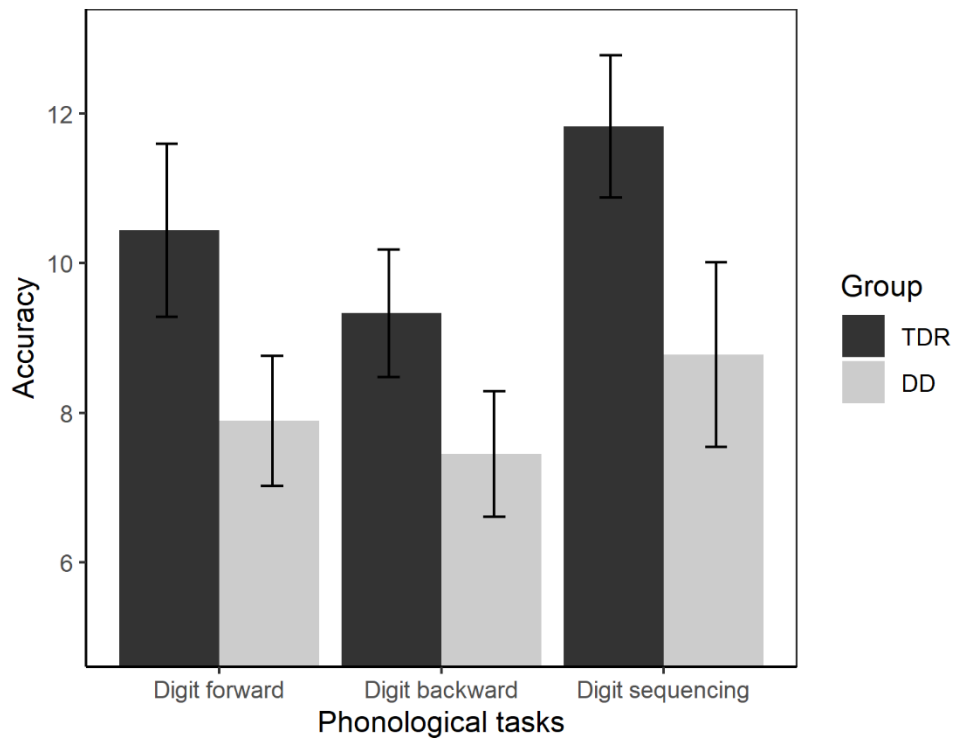
Figure 8. Accuracy on phonological tasks. Error bars represent standard errors. TDR = typically developing readers, DD = developmental dyslexics.
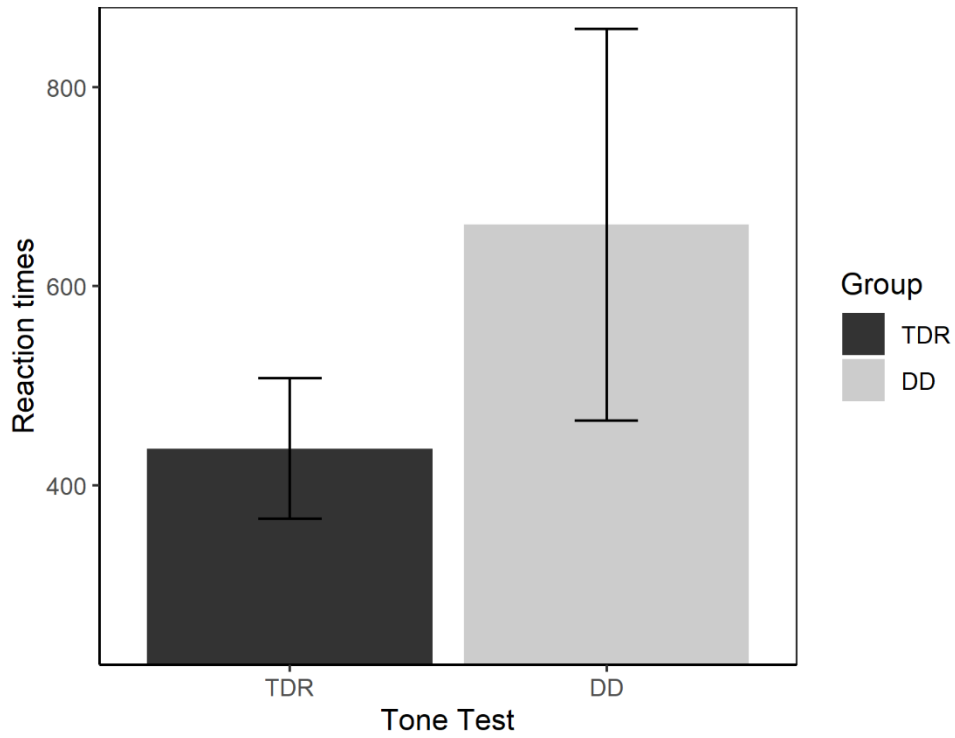
Figure 9. Reaction times on auditory tasks. Error bars represent standard errors. TDR = typically developing readers, DD = developmental dyslexics.
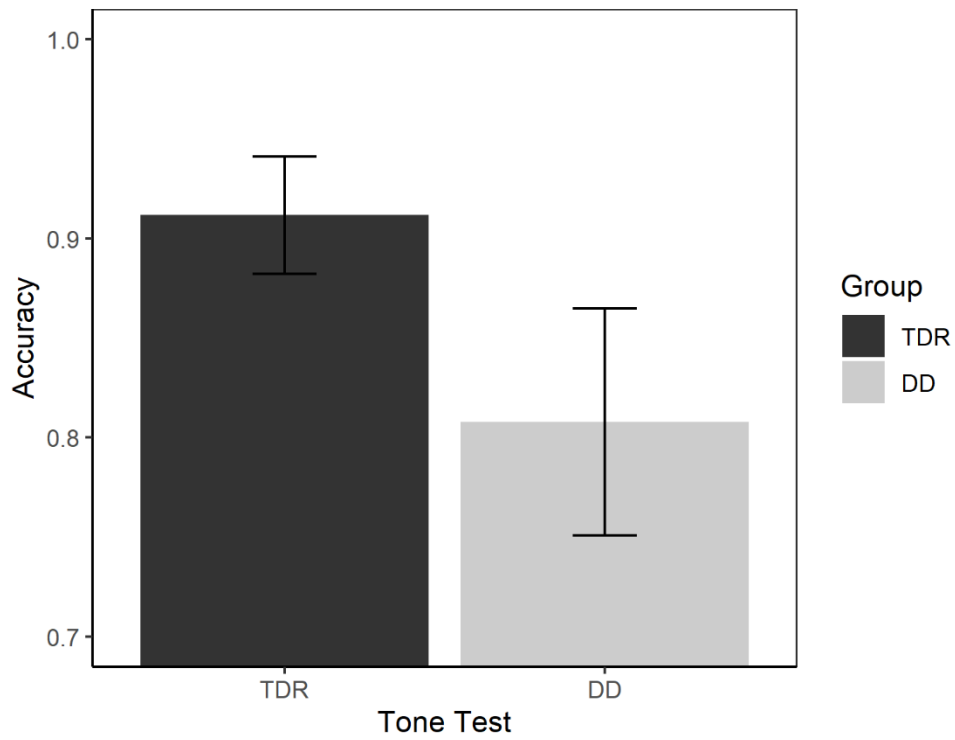
Figure 10. Accuracy on auditory tasks. Error bars represent standard errors. TDR = typically developing readers, DD = developmental dyslexics.

Table 1. Mean and standard deviations (*SD*) in all tasks.

Task	DD	TDR	Statistical analyses		
			F(1, 34)	*p*	*η²p*
VSWM					
Balloons	30.61(4.41)	33.33(3.38)	4.32*	.045	.113
Sequential Matrices	35.17(10.57)	48.17(8.62)	16.35**	.000	.32
Simultaneous Matrices	56.61(6.90)	61.83(5.61)	6.20*	.018	.15
Visual					
Checkerboards RTs	2866.34(853.49)	2334.52(525.50)	5.07*	.031	.130
Kanji RTs	1826.27(558.80)	1411.08(331.28)	7.35*	.010	.178
Checkerboard ACC	0.94(0.03)	0.96(0.04)	1.90	.177	.053
Kanji ACC	0.95(0.04)	0.97(0.02)	1.81	.187	.051
Phonological					
Span test	24.20(4.50)	31.61(4.34)	25.18**	.000	.426
Auditory					
Tone test RTs	661.70(395.60)	436.10(141.68)	5.15	.030	.131
Tone test ACC	0.81(0.11)	0.91(0.06)	11.66**	.002	.255

Note. TDR = typically developing readers; DD = developmental dyslexics; RTs = reaction times; ACC = accuracy; .000 means that the value is zero when approximated to the third decimal. ∗ *p* < .05, ∗∗ *p* < .01.

Table 2. Mean (M) and standard deviations in four conditions of the checkerboards and Kanji tasks.

Task	DD		TDR	
	M	*SD*	**M**	*SD*
Checkerboards				
Accuracy				
High complexity & high discriminability	.98	.03	1.00	.01
High complexity & low discriminability	.87	.13	.91	.11
Low complexity & high discriminability	.99	.02	.99	.04
Low complexity & low discriminability	.95	.07	.96	.05
Reaction time				
High complexity & high discriminability	1838.35	535.87	1417.54	344.43
High complexity & low discriminability	6792.15	2630.16	5445.70	1530.99
Low complexity & high discriminability	1523.55	407.04	1207.07	202.48
Low complexity & low discriminability	1763.09	487.41	1428.18	249.58
Kanji				
Accuracy				
High complexity & high discriminability	.98	.03	.98	.03
High complexity & low discriminability	.91	.10	.97	.03
Low complexity & high discriminability	.99	.02	.99	.03
Low complexity & low discriminability	.95	.05	.94	.05
Reaction time				
High complexity & high discriminability	1669.79	518.22	1299.83	282.70
High complexity & low discriminability	2608.45	889.87	1932.24	541.32
Low complexity & high discriminability	1204.08	328.79	952.65	171.30
Low complexity & low discriminability	1912.30	714.05	1482.72	436.28

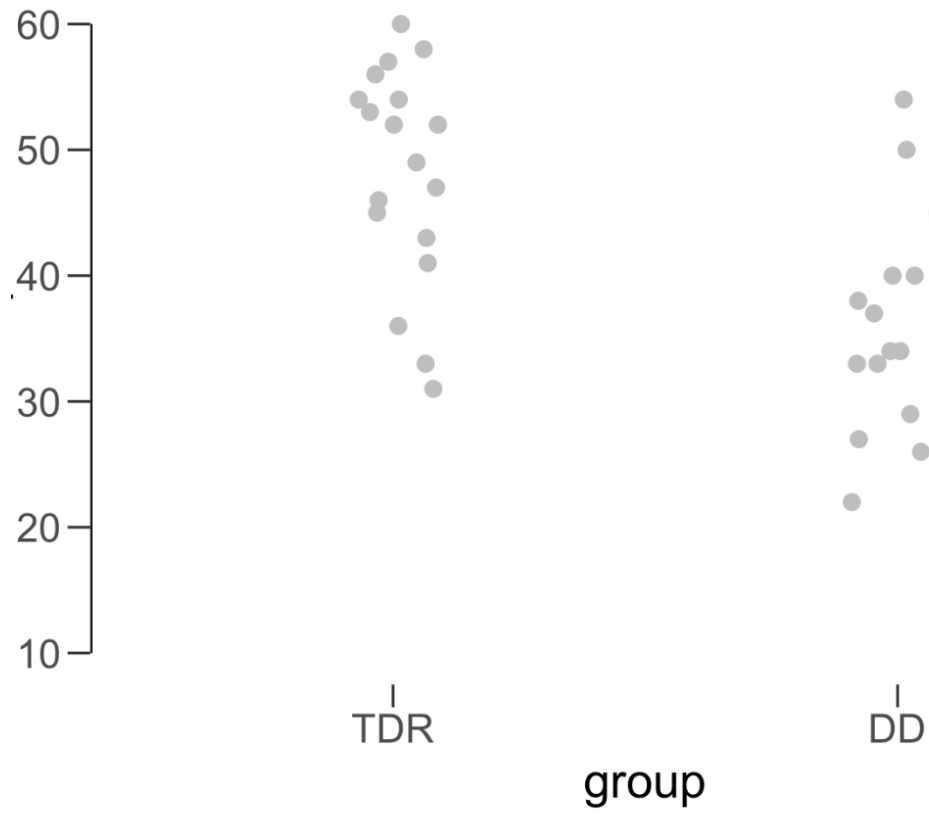*Note.* TDR = typically developing readers; DD = developmental dyslexics.

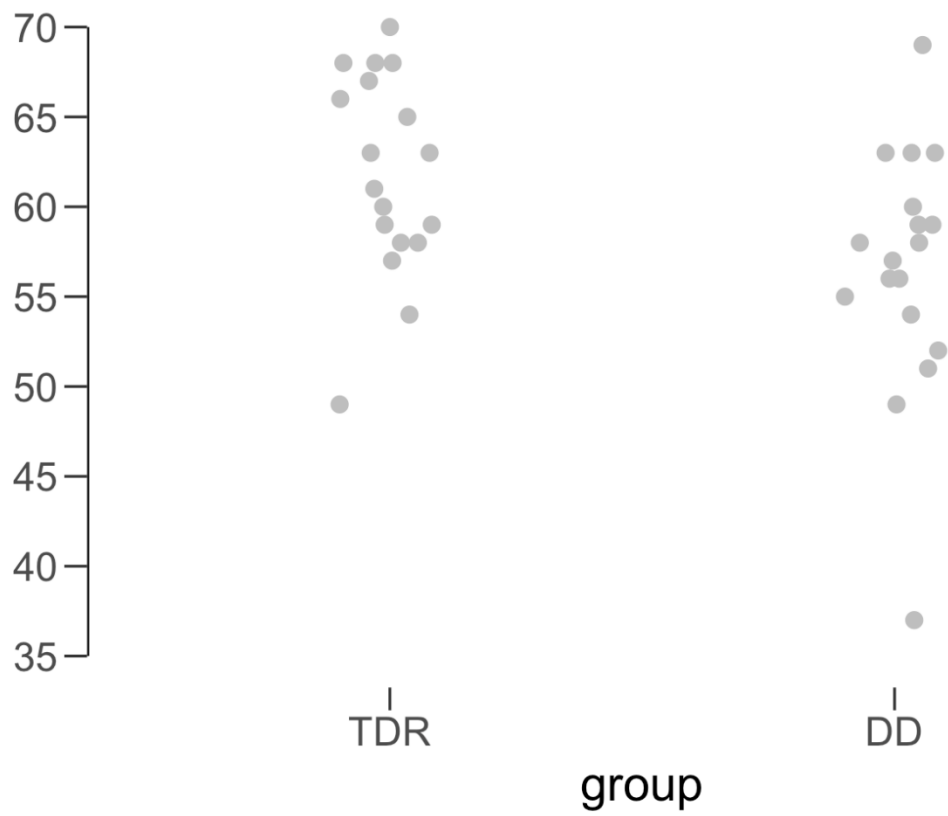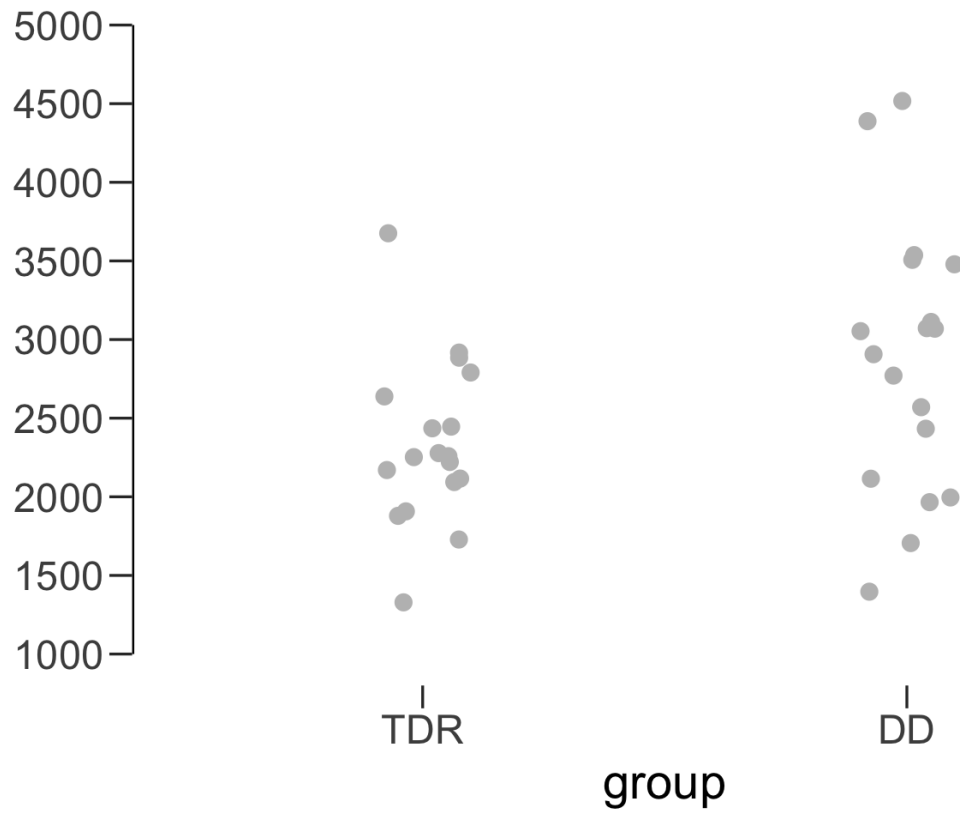Graphic representation of the pattern of results shown by each participant across all tasks.
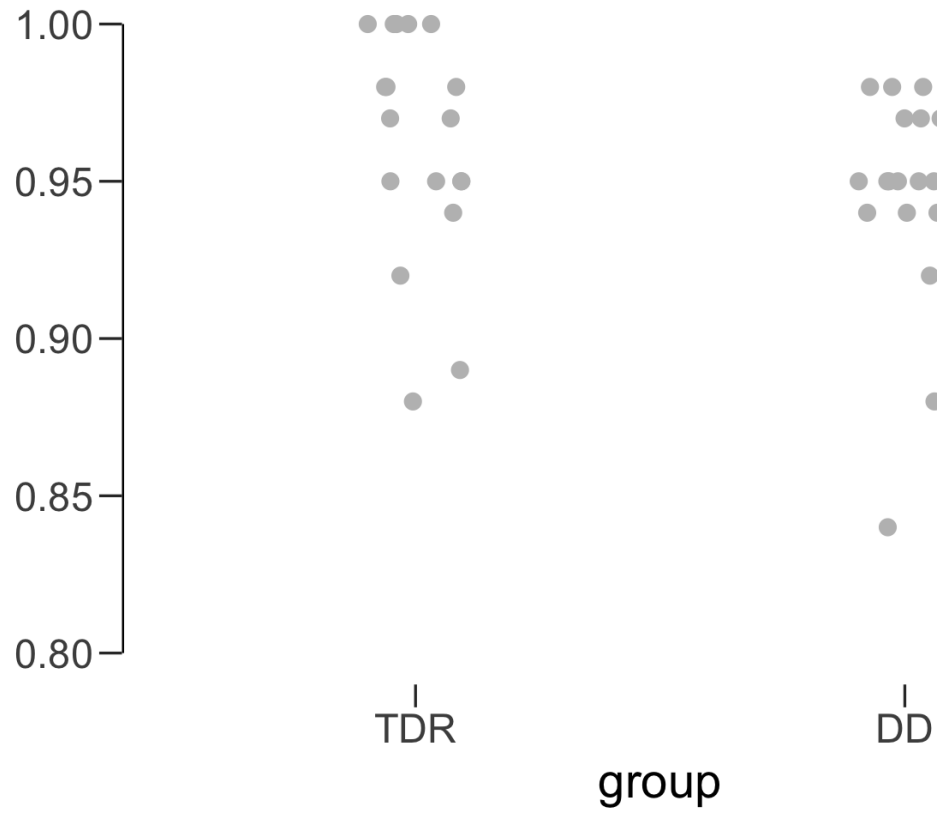
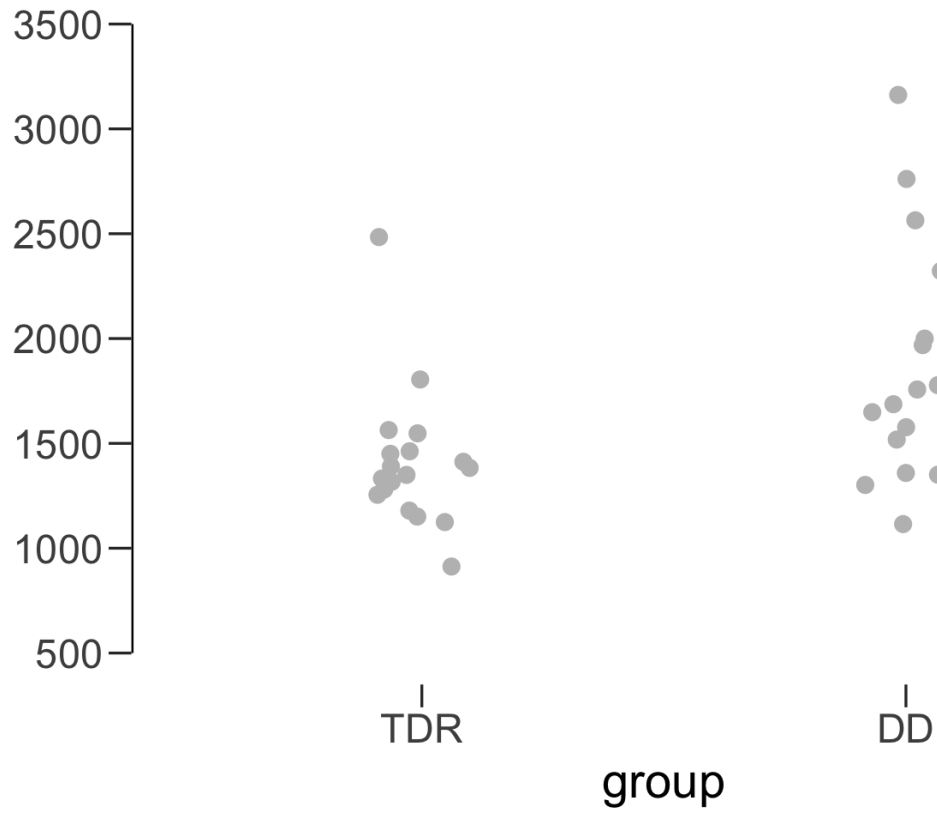**Balloons**
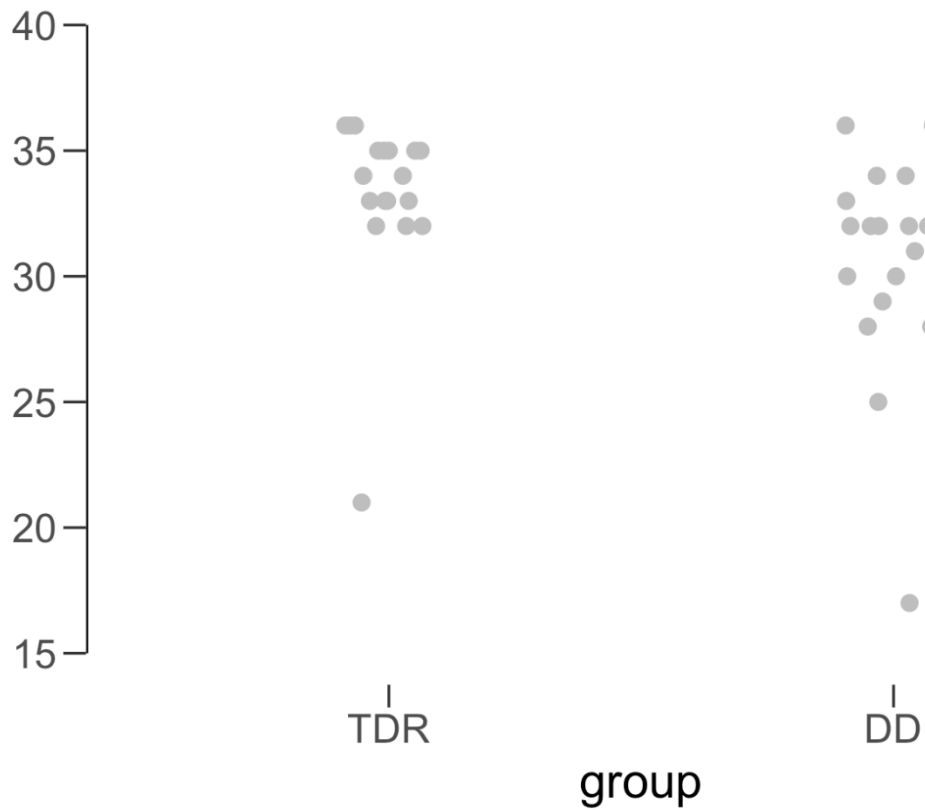
Sequential matrices

Simultaneous matrices

Checkerboard reaction times

Checkerboard accuracy

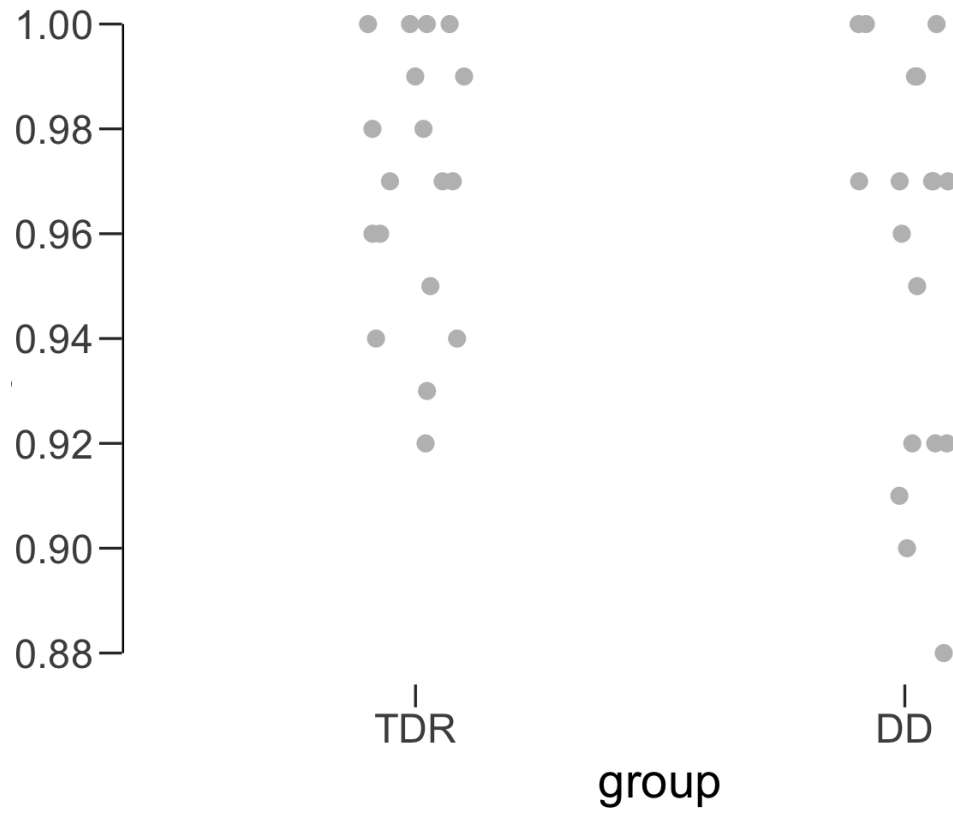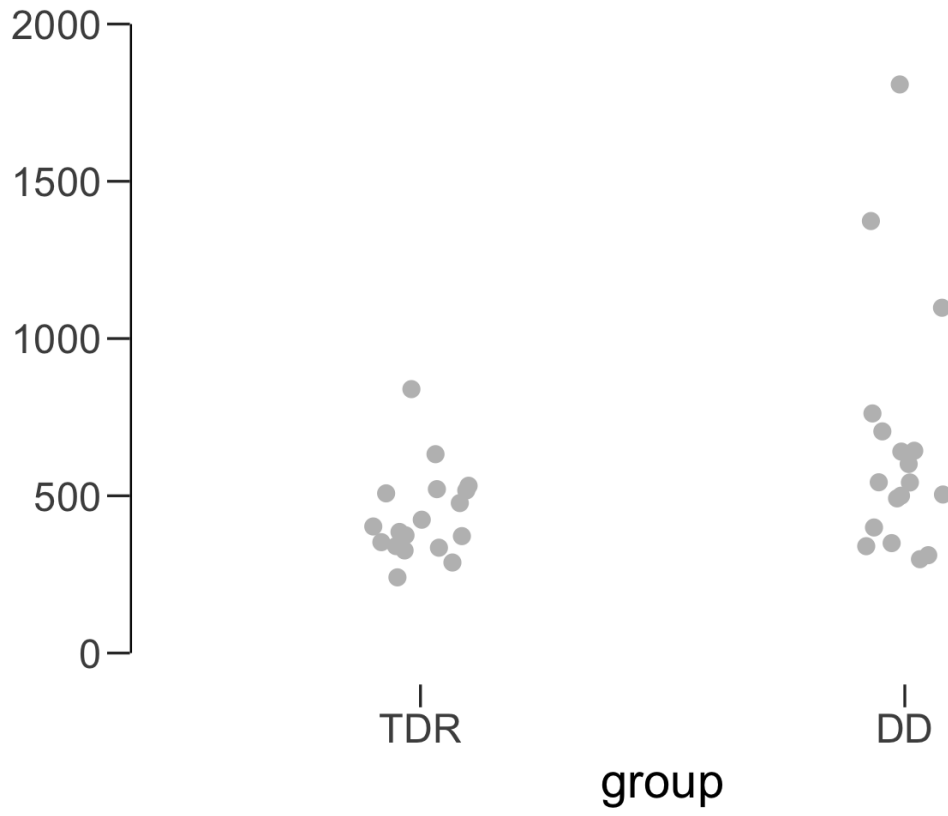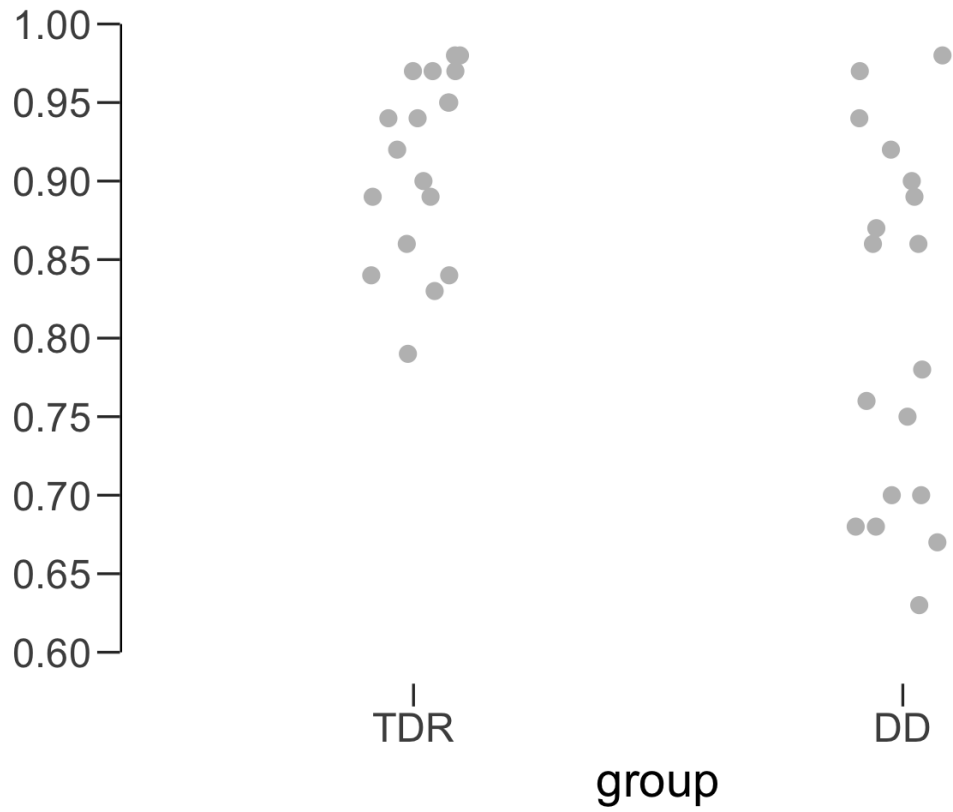**Kanji reaction times**

Kanji accuracy

Tone test reaction times

Tone test accuracy

Digit span