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Heterogeneity of short-term memory deficits in children with dyslexia

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Many studies have highlighted short-term memory (STM) impairment in dyslexic individuals. Several studies showed deficits for both item and serial order aspects of verbal STM in dyslexic individuals. These group-based studies, however, do not inform us about the prevalence of these deficits and, importantly, their potential heterogeneity at the individual level. The present study examined both group-level and individual STM profiles in dyslexic and age-matched non-dyslexic children. While confirming previous group-based results of both item and serial order STM deficits, individual analyses indicated two distinct profiles: one profile was associated with verbal item STM and phonological impairment while another profile showed selective serial STM deficits in both verbal and visual domains. Our results highlight the need for practitioners to consider the heterogeneous nature of STM impairment in dyslexia and to adapt STM and reading treatment strategies accordingly.

KEYWORDS
dyslexia, phonological processes, serial order, short-term memory

Practitioner Points

- Our results demonstrate an important heterogeneity of short-term memory (STM) deficits in children with dyslexia
- About 50% of dyslexic children present a significant STM deficit
- Serial order and item STM deficits may occur independently, the latter being more systematically associated with phonological impairment

1 | INTRODUCTION

Developmental dyslexia is characterized by severe and persistent difficulties with accurate or fluent word recognition and spelling despite adequate instruction, intelligence and sensory abilities (Peterson & Pennington, 2015). A common explanation of this neurodevelopmental disorder involves a phonological processing deficit (Ramus et al., 2013). However, developmental dyslexia is also characterized by short-term memory (STM) impairment (Gathercole et al., 2016; Jeffries & Everatt, 2004; Menghini et al., 2011; Tiffin-Richards et al., 2008), and several recent studies have suggested that this impairment may concern more particularly the serial order aspects of STM, in both verbal and visuo-spatial domains (Majerus & Cowan, 2016). These STM deficits in dyslexia are well documented at the group level, however, data in children with dyslexia exploring individual differences are much less abundant. Furthermore, due to the heterogeneity of the results obtained in the group studies and the methodological differences, the question of whether individual profiles underlie the group differences remains open for debate. The aim of the present study was to investigate item and serial order STM abilities in children with dyslexia, by examining both group-level and individual profiles, and to further examine the potential heterogeneity of STM deficits in dyslexia.

1.1 | The distinction of item versus serial order information in STM

At the theoretical level, several models of STM consider that the temporary storage of item information (item STM) and the storage of serial order information (serial order STM) are supported by distinct mechanisms (Attout et al., 2018; Burgess & Hitch, 1999; Burgess & Hitch, 2006). Item STM involves the storage of the verbal items as well as their phonological and lexico-semantic characteristics, and as such, is considered to interact strongly with the language knowledge base (Majerus, 2009; Saint-Aubin & Poirier, 1999). In contrast, serial order STM allows for the storage of the serial order in which items were presented, and serial order coding has been proposed to rely on spatial, temporal or other contextual codes (Abrahamse et al., 2014; van Dijck et al., 2013). The item-order distinction is also supported at the neural level, with distinct fronto-temporal and fronto-parietal networks supporting item and serial order coding in STM (Attout et al., 2019; Kalm & Norris, 2014; Majerus et al., 2010; Marshuetz et al., 2000; Papagno et al., 2017). Dissociations between serial order STM and item STM capacity have also been observed in children and adults with different neurodevelopmental and neurological disorders (Schraeyen et al., 2019). The distinction between item and serial order STM abilities has important functional implications as serial order STM has been shown to be a specific predictor of lexical and reading abilities, as compared to item STM (Leclercq & Majerus, 2010; Martinez Perez, Majerus, Mahot, & Poncelet, 2012; Martinez Perez, Majerus, & Poncelet, 2012; Ordonez Magro et al., 2020, 2021), and this particularly for the early phase of reading acquisition when reading is still characterized by a sequential, letter-by-letter decoding strategy. It thus appears important to examine the nature of item versus serial order STM impairment in dyslexia, as the presence of serial order STM impairment may further hinder reading acquisition in this population.

1.2 | Phonological and STM deficits in dyslexia

Phonological processing involves a set of different cognitive processes, from speech perception to metacognitive processes such as phonological awareness (Loucas et al., 2016). The lowest level of phonological processing corresponds to the automatic perception of phonetic and phonological features of speech stimuli (Gombert, 1992). It is typically assessed via minimal pair discrimination tasks, when individuals have to recognize whether two verbal stimuli differ or not at the phonetic level (Le Jan et al., 2011). The highest level corresponds to meta-phonological processing, characterized by explicit cognitive control over phonological units. Phonological awareness is generally assessed via spoonerisms, phonemic segmentation or phoneme deletion tasks (Gombert, 1992).

The phonological deficit hypothesis considers that dyslexia is the result of dysfunctional phonological representations or processes (Thomson & Goswami, 2008). Ramus and Szenkovits (2008) argued that phonological impairment in dyslexia corresponds to meta-phonological difficulties, which they referred to as a phonological access deficit, when individuals have to do explicit and complex mental manipulations on speech sounds with a high short-term memory load. Also note that phonological deficits are not necessarily restricted to dyslexia. McArthur et al. (2000) showed that comorbidity between developmental language disorder and dyslexia is frequent (nearly 50%), with phonological awareness deficits in both cases (De Groot et al., 2015). At the same time, some studies have shown that phonological processing impairments were nevertheless more strongly associated with dyslexia than with developmental language disorder (Catts et al., 2005; Spanoudis et al., 2019). McArthur and Castles (2013) observed that dyslexic children showed a deficit in phonological discrimination and phonological awareness, but not children with only a developmental language disorder. Nithart et al. (2009) also observed opposed profiles, with both groups presenting impairment of phonological awareness while children with developmental language disorder also presented a deficit for speech perception as revealed by a phonetic discrimination task.

Regarding STM more specifically, deficits in verbal STM are frequently shown in dyslexic individuals (Berninger et al., 2009; Gathercole et al., 2006; Peng et al., 2018; Swanson et al., 2009, 2010; Wang & Gathercole, 2013). A number of authors consider that these deficits are the consequence of the phonological processing deficit that characterizes dyslexia (Kibby, 2009). Studies distinguishing serial order and item STM components provide a more nuanced view. Administered to children with dyslexia a single nonword repetition task to assess the storage of phonological item information and a serial order reconstruction task to assess serial order STM. The authors observed both item and serial order STM deficits, nevertheless these deficits appeared to be independent. Children with dyslexia presented a serial order STM deficit relative to both chronological age and reading age-matched control groups while the item STM deficit was only observed relative to the chronological age-matched control group. Both item and serial order STM impairments were also observed by Staels and Van Den Broeck (2014) in children with dyslexia, but, using different analyses, they did not find evidence for an independence of both types of STM impairment. Their results thus raised questions about the specificity of the serial order STM deficits in dyslexia. A more recent study observed again specific serial order STM deficits in dyslexia, and this for both verbal and nonverbal serial order STM tasks while verbal item STM was preserved (Hachmann et al., 2020).

Studies distinguishing order and item STM components have also been conducted in adults with dyslexia. Martinez Perez et al. (2013) showed independent STM impairment in dyslexic adults for item STM and serial order STM components in the verbal domain. In contrast, one study suggested that serial order and item STM deficits were inconsistent in university students with self-reported dyslexia (Wang et al., 2016). Schraeyen et al. (2019), using a nonword repetition task, furthermore showed that poor performance of dyslexic individuals on this task was characterized by serial order errors (phoneme migration errors) rather than phoneme identity errors. Similar findings were observed by Romani et al. (2015) for the visual STM domain, with specific difficulties for sequential versus simultaneous presentation formats of memoranda.

Studies conducted in children and in adults with dyslexia have directly compared verbal and visual STM tasks and provided evidence for serial order STM deficits in both domains (Cowan et al., 2017; Hachmann et al., 2014; Laasonen et al., 2012), with furthermore, at the neural level, reduced involvement of intraparietal cortices in the right hemisphere (Martinez Perez et al., 2015).

In sum, a large amount of studies have highlighted STM impairment in dyslexic individuals. These deficits appear to involve impairment at both item and serial order levels of STM, at least at the group level. At the same time, the question of the specificity of these deficits remains unclear, with some inconsistency regarding the presence of serial order STM deficits, raising the question of a possible heterogeneity of the nature of STM deficits in dyslexia. On the one hand, given the dependency of verbal item STM on phonological processing abilities (Majerus, 2009; Saint-Aubin & Poirier, 1999) and given the high prevalence of phonological processing deficits in dyslexia (Catts et al., 2005), we may expect a high proportion of children with dyslexia presenting also with verbal item STM deficits. Martinez Perez, Majerus, Mahot, and Poncelet (2012); Martinez Perez, Majerus, and Poncelet (2012) indeed showed a strong correlation between verbal item STM and phonological awareness abilities in typically developing children. On the other hand, serial order STM deficits may either be an associated deficit going in parallel with item STM deficits, with difficulties in encoding item information also leading to difficulties in encoding order information. Alternatively, serial order STM deficits may present an additional deficit whose severity is independent of the severity of the item STM. The latter situation is particularly important to consider given that, as noted earlier, previous studies have shown that serial order STM abilities are an important predictor of verbal learning abilities, including the early stages of reading acquisition (Leclercq & Majerus, 2010; Martinez Perez, Majerus, Mahot, & Poncelet, 2012; Martinez Perez, Majerus, & Poncelet, 2012; Ordonez Magro et al., 2020, 2021). If the latter situation is observed, then the serial order STM impairment could be considered to be an additional factor contributing to the reading acquisition difficulties in children with dyslexia. In that case, treatment strategies of dyslexia should also target specifically serial order STM abilities, particularly for those children presenting with specific deficits for this aspect of STM. On the other hand, if the item STM deficit is predominant and goes in parallel with phonological processing deficits, treatment strategies focusing on phonological processing abilities may be sufficient, item STM being dependent on phonological processing abilities. In other words, in order to determine optimal treatment strategies, it is important to understand the individual STM profiles of children with dyslexia.

1.3 | The current study

The present study re-examined item and serial order STM as well as phonological processing abilities in children with dyslexia by focusing specifically on individual STM profiles in order to determine the extent to which item and serial order STM deficits are associated or can dissociate in children with dyslexia. However, for sake of comparison with previous studies that focused exclusively on group-level analyses, we additionally provide group-level analyses.

Item and serial order STM abilities were measured using tasks that have been shown to distinguish these two aspects of STM in previous studies in children and adults with or without dyslexia (Leclercq & Majerus, 2010; Martinez Perez, Majerus, Mahot, & Poncelet, 2012; Martinez Perez, Majerus, & Poncelet, 2012; Martinez Perez et al., 2013). At the item level, these tasks included a single-item delayed repetition task as well as item recall scores for word and nonword lists in an immediate serial recall task. Serial order retention and recall abilities were measured via a serial order reconstruction task as well as order recall scores for the immediate serial recall task. Furthermore, we added a visual serial order reconstruction task in order to determine the existence of a possible domain-general deficit in serial order STM abilities, as discussed above. Phonological processing was assessed with two tasks distinguishing perceptual processing from metaphonological awareness. Phonetic perceptual abilities were assessed via two minimal pair discrimination tasks. Metaphonological awareness was assessed using phoneme deletion tasks.

Given that the aim of this study was to examine phonological and STM deficits and their prevalence and heterogeneity at the individual level rather than determining core and potentially causal deficits of dyslexia, we compared our sample of dyslexic children to participants that were individually matched on age, nonverbal reasoning and receptive vocabulary (but not reading level).

2 | METHOD

2.1 | Participants

Sixty native French-speaking children initially participated in the present study, but five dyslexic children were subsequently excluded due to failure to meet the inclusion criteria. Of these five children, two had comorbid developmental language disorder according to the speech and language assessment report. Two other children had ADHD comorbidity and one had an abnormal range non verbal IQ as measured by the Raven Coloured Matrices.

The final sample comprised a group of 25 dyslexic children (14 boys and 11 girls; age $M = 146.9$ months, $SD = 17.6$), compared to a group of 30 control children without reading disorders (17 boys and 13 girls; age $M = 146.9$, $SD = 20.1$). All dyslexic children had received a formal diagnosis of dyslexia by practitioners (i.e., speech therapist, neuropsychologist, neuropediatrician or school doctor). In addition, as shown in Table 1, their reading age was at least 18 months below their chronological age according to a standardized French reading test (Lefavrais, 2005). The dyslexic children and the control children were individually matched on age, $t(53) = 0.001$, $p = 0.999$, nonverbal reasoning (Raven et al., 1998), $t(53) = 1.88$, $p = 0.064$, and receptive vocabulary (Dunn et al., 1993), $t(53) = 1.731$, $p = 0.089$, but differed on reading age as expected, $t(53) = 13.12$, $p < 0.001$. The characteristics of both groups are shown in Table 1.

All participants were Native French speakers and attended a regular school setting in France. Participants were recruited from schools in the regions of Normandy and Brittany. In these schools, dyslexic children were recruited from special programmes for students with specific learning disorders. Socio-economic status was determined based on the parents' profession and the INSEE (2020) classification. Forty-eight percent of the mothers of children with dyslexia were classified as 'managers and higher intellectual professions' compared to 36% of the mothers in the control group, and 52% of the mothers of children with dyslexia were classified in the other categories (craftsmen, intermediate professions, employees, workers) compared to 63% in the control group., 56% of the fathers of children with dyslexia were classified as 'managers and higher intellectual professions' compared to 40% of the fathers in the control group, and 44% of the fathers of children with dyslexia were classified in the other categories (craftsmen, intermediate professions, employees, workers) compared with 60% in the control group. Professions associated with higher socio-economic status were slightly more frequent in the group of children with dyslexia. A parental questionnaire and a retrospective analysis of the medical records including multidisciplinary assessments were used for the information about children's hearing/vision/and ADHD/psychiatric history. All children had normal or corrected-to-normal vision, normal hearing level and none of them presented a history of neurological, psychiatric disorder, or attention-deficit hyperactivity disorder. Children with a comorbid language impairment were excluded from the study, based on the speech therapists' language assessment reports provided to us by the parents. A note detailing the procedure of the study was provided to all participants and their parents. Informed consents were obtained from children and parents before the children participated in the study. The present study complies with the terms defined by the World Medical Association in the Declaration of Helsinki regarding ethical principles applicable to research involving human beings, as well as with the specific ethical and legal procedures regarding psychological experiments of the Université Rennes 2.

2.2 | Materials

2.2.1 | Background tasks

General nonverbal reasoning abilities were measured using Raven's Coloured Progressive Matrices (Raven et al., 1998). This task has a high internal consistency test-retest reliability (Cronbach α: 0.85–0.93; Abdel-Khalek, 2005). The

TABLE 1 Characteristics of the dyslexic and control groups (means and standard deviations).

	Dyslexics	Controls
Chronological age (years; months)	12;2 (1;5)	12; 2 (1;8)
Reading age (years; months)	7;9 (1;2)	12;4 (1;4)
Nonverbal reasoning (standardized score)	100.1 (11.5)	105.9 (11)
Receptive vocabulary (standardized score)	111.3 (10.4)	116.3 (10.7)

standardized scores were used. The *Echelle de Vocabulaire en images Peabody* (Dunn et al., 1993) was administered to control for receptive vocabulary knowledge; this scale is a French adaptation of the Peabody Picture Vocabulary Test. We used standardized vocabulary scores. This task has high test–retest reliability (R = 0.80; Dunn et al., 1993). The standardized French reading test « Alouette-R » (Lefavrais, 2005) estimated reading level. This test requires reading a text composed of 265 words and containing many low-frequency words. Children were requested to read the text as fast and accurately as possible. A reading accuracy score and a reading speed score were calculated, and they were additionally converted into reading age in months, based on the normative data provided by Lefavrais (2005).

2.2.2 | Phonological processing

Phonetic perception was assessed via two versions of a minimal pair discrimination task (Attout et al., 2012; Majerus et al., 2005). Fifty-six pairs of nonsense CV syllables were presented via headphones, at standard (28 pairs) or accelerated (stimuli generated via the TD-PSOLA® algorithm implemented in Praat) (28 pairs) speech rates for the two versions. In each condition, 14 pairs were identical (e.g., /ra-ra/) and 14 pairs had a different initial consonant. When the initial consonants were different, they differed by one phonetic feature, either voicing (10 pairs) (e.g., /pa-ba/) or place of articulation (18 pairs) (e.g., /ta-pa/). The vocalic context remained constant for all pairs (/a/). All stimuli had been recorded by a female native French speaker. The children were asked to listen carefully to each syllable pair and to determine whether they are identical or not by responding 'yes' or 'no'. The dependent variable used for the group-level analyses was the proportion of correct responses over the two versions of the entire task, with an internal consistency reliability of $\alpha = 0.64$. For individual-level analyses, the scores for the two versions were considered separately in order to compute composite z-scores reflecting the individual level of deficit in the most representative manner (see below).

Phonological awareness was assessed via a phoneme deletion task taken from the EVALEC computerized battery designed to assess reading and phonological processing skills (Sprenger-Charolles et al., 2005). Children listened to a nonword and had to delete the first sound and pronounce the remaining part of the nonword. Thirty-four pseudowords were presented via headphones, including 10 tri-syllabic pseudowords, 12 monosyllabic pseudowords with a consonant-vowel-consonant structure (C-V-C), and 12 monosyllabic pseudowords with a consonant-consonant-vowel structure (C-C-V). This task included a tri-syllabic nonword score, a monosyllabic nonword C-V-C score and a monosyllabic nonword C-C-V score. Again, the dependent variable used for the group-level analyses was the proportion of correct answers on the 34 nonwords of the task with an internal consistency reliability coefficient of $\alpha = 0.77$, while the scores for three subconditions were considered separately for the computation of composite z-scores for individual level analyses (see below).

2.2.3 | STM for item information

STM for item information was assessed using two tasks. The first task was an item delayed repetition task (Leclercq & Majerus, 2010; Majerus, Poncelet, Elsen, & van der Linden, 2006; Majerus, Poncelet, Greffe, & van der Linden, 2006). A total of 30 single monosyllabic nonwords were presented separately via headphones to the children. At the end of each stimulus, the children had to repeat the nonword to confirm that they had correctly perceived the item and immediately after they were instructed to count in steps of 2 for 6 s. Then the experimenter asked the children to repeat the stimulus. This task was administered using Open Sesame (Mathôt et al., 2012). The dependent variable was the proportion of nonwords correctly repeated after the 6 s delay. High test–retest reliability estimates were obtained for the item delayed repetition task by Majerus, Poncelet, Greffe, and van der Linden (2006), where the test–retest correlation was 0.74. This task was designed to maximize the processing demands of phonological item information and to reduce serial order requirements given that a single, unfamiliar, monosyllabic item had to be repeated.

The second task was an Immediate Serial Recall (ISR) task for word and pseudoword lists. Children were asked to recall lists of words and pseudwords in the same order as during their presentation. The words were mono-syllabic (C-V-C), with a mean lexical frequency of 127.80 (range 0.73–523) (New et al., 2004) and a mean imageability rating of 5.10 (range 1.60–6.70) based on a rating scale ranging from 1 (low) to 7 (high) (Bonin et al., 2011). The pseudowords were also mono-syllabic (C-V-C), with a mean phonotactic frequency of 771.10 (range 12–3318) for diphones CV and a mean of 788 (range 17–2555) for diphones VC. These phonotactic frequencies were determined using the French phonetic database by Tubach and Boë (1990). In total, 32 lists were presented ranging from 2 to 5 items in length, with four lists per sequence length. The lists were presented auditorily at the rate of one item every 1 s. The item recall measure was calculated by determining the proportion of items correctly recalled independently of their serial position, relative to the total number of items to be recalled, with an internal consistency reliability coefficient of $\alpha = 0.71$ in ISR task for nonwords and an internal consistency reliability coefficient of $\alpha = 0.74$ in ISR task for words. This task, as well as all other tasks, were scored by the same experienced neuropsychologist trained in the administration and scoring of language-related tasks. A non-word was considered correct only if every phoneme was pronounced correctly.

Note that previous validation and correlation studies have shown that the item delayed repetition task presents a specific association with other phonological processing tasks and that both the item delayed and immediate serial recall tasks show a strong dependency on access to item level linguistic information, in contrast to the serial order STM measures reported below (Hulme et al., 1991; Majerus, Poncelet, Greffe, & van der Linden, 2006; Majerus et al., 2008; Martinez Perez, Majerus, Mahot, & Poncelet, 2012; Martinez Perez, Majerus, & Poncelet, 2012). Word and nonword versions of these tasks are also highly correlated (e.g., Majerus, Poncelet, Greffe, & van der Linden, 2006).

2.2.4 | STM for order information

STM for serial order information was assessed for both verbal and nonverbal materials, using two serial order reconstruction tasks. The first task was an adaptation of the serial order reconstruction task used. It consisted of the auditory presentation of digit lists of increasing length. Each list contained 4–7 digits, sampled from digits 1–7. For a list of length N, only the first N digits were used (e.g., for a list of length 4, the digits 1, 2, 3 and 4 were presented in each trial). For a given sequence length, only the order of the digits varied between trials. After a list was presented, children were requested to reconstruct the order of presentation of the digits, by using cards on which the digits were printed, and by arranging them horizontally on the desk. The number of cards given to the participants corresponded exactly to the number of digits used in the lists for each sequence length. In total, 24 lists were presented ranging from 4 to 7 items in length, with six lists per sequence length. The test-retest reliability was moderate-to-strong with $R = 0.68$ (Leclercq & Majerus, 2010).

To assess STM for serial order information independently of verbal abilities, we also used a STM for order information task in a nonverbal modality. This task was an adaptation of the nonverbal serial order reconstruction task used by Hachmann et al. (2014), administered using Open Sesame (Mathôt et al., 2012). It consisted of the visual presentation of nonsense drawings in lists of increasing length. Each list contained 4–7 drawings. For each list length, the same drawings were presented and only their order varied. For each trial in a given sequence length, the same drawings were presented and only their order varied. For a list of length $N + 1$, the same drawings as for list length N were used plus one new drawing. As in the verbal serial order task, children responded by horizontally arranging cards representing the drawings on the desk. The procedure of the two tasks, with the same predictable stimuli used in each trial, ensured that processing and maintenance of item information were minimized while the task requirements maximized serial order processing, retention and recall. For both serial order reconstruction tasks, the dependent measure was the proportion of items placed in the correct serial position across all trials, with an internal consistency reliability coefficient of $\alpha = 0.88$ for the nonverbal serial order reconstruction task.

Finally, we computed a serial order recall measure for the word/pseudoword immediate serial recall task described in the previous section by calculating the proportion of items recalled in correct serial position relative to the overall amount of items that were recalled, allowing us to obtain a serial order recall measure corrected for differences in item recall abilities. Serial order recall measure for nonwords showed a reliability coefficient of $\alpha = 0.79$ and serial order recall measure for words showed a reliability coefficient of $\alpha = 0.77$.

Note that previous validation studies have shown that the serial order reconstruction task used here shows a specific correlation with order but not item errors in word and nonword recall tasks (Majerus & Boukebza, 2013; Majerus, Poncelet, Elsen, & van der Linden, 2006).

2.2.5 | General procedure

The children were assessed individually in a quiet room in their school or at home. The tasks were administered in a fixed order. The tasks were presented in two separate sessions each lasting approximately 1 h30 and included measures that are not developed in this study.

2.2.6 | Data analysis

We conducted four sets of analyses. The first set of analyses tested whether the group of dyslexic children differed from the group of control children, for all measures collected in the study. This was done separately for each task, using generalized linear mixed model analyses on item-level data to account for variability between items. To account for both item-level and participant-level variation, random intercepts for both items and participants were included in the model. The analyses assumed a normal distribution for tasks scored as a proportion correct per trial (the two ISR tasks and the two serial order reconstruction tasks) and a binomial distribution for tasks scored 0–1 (the two phonological processing tasks and the item delayed repetition task). To control for differences in cognitive ability and vocabulary between the two groups, scores on Raven's matrices and the EVIP were included as covariates in the analyses.

These analyses were conducted using package lme4 (Bates et al., 2015) for R (R Core Team, 2022). Tested (general) linear mixed models were of the form 'item score $\sim 1 + (1|\text{participant}) + (1|\text{item}) + \text{Raven} + \text{EVIP} + \text{group}$'. Statistical tests were performed by comparing a model with group as a predictor, to a restricted model without group as a predictor, using a chi-squared test. This analysis involved nine different tests; to control for inflation of type I error due to multiple comparisons, p-values were also corrected using Benjamini-Hochberg correction for false discovery rate (FDR; Benjamini & Hochberg, 1995).

The second set of analyses compared the extent of the difference between the two groups of children for pairs of critical tasks based on the variables manipulated in this study (phonological abilities vs. short-term memory; short-term memory for item information vs. short-term memory for serial order information; See also below for further justification of the pairs of tasks to be contrasted). These analyses could not be performed at the item level and were instead done at the level of total task scores. We used mixed-design analyses of covariance (ANCOVAs), with group as a between-subjects variable (dyslexic vs. control), and task as a within-subjects variable (e.g., phoneme deletion task vs. minimal pair discrimination task), again including scores on Raven's matrices and the EVIP as covariates. The test of interest was the interaction between group and type of task.

The third set of analyses tested the specificity of the group effects observed in the previous analyses, by determining whether the group effects for a given task remained significant after controlling for another critical task (i.e., do serial order short-term memory deficits remain significant after controlling for item short-term memory deficits; see below for further justification). These analyses were conducted using the same design outlined for the previous set of analyses, but with additional covariates. These covariates are detailed separately for each analysis in the Results section.

Lastly, the fourth set of analyses used the approach of a multiple case study and examined individual levels of deficit for each task in each dyslexic child. We used age-corrected z-scores for determining individual deficit levels rather than an inferential statistical approach such as Crawford and Howell's modified t-tests, which require comparing the score of a given participant to the average of the control group (Crawford & Howell, 1998). The latter procedure, although specifically designed for single case studies, would have been problematic here given the age range of the dyslexic and control groups. Proper use of this procedure would have required dividing the control group into multiple subsamples with a narrow age range and of small size, introducing discontinuity errors (e.g., child aged 9 years 11 months would have been compared to a different subsample and a different performance level than a child aged 10 years of age while the actual difference in age between the two is minimal) (Lenhard et al., 2019).

Instead, we used a regression-based norming approach (Zachary & Gorsuch, 1985). This method has the advantage that it can be used with a smaller sample size than a traditional norming approach (Oosterhuis et al., 2016). The following steps were applied (see van Breukelen & Vlaeyen, 2005). Performance in a given task was regressed on age in the whole control group ($n = 30$); the parameters of this regression were used to predict the expected score of each dyslexic child given their age; the discrepancy between actual and expected scores was retrieved and divided by the standardized residuals of the regression for the control group. For each dyslexic child, this procedure yielded a z-score reflecting their standardized distance to the expected score based on chronological age and associated performance in the control group. Since the distributions of all variables were normal or close to normal, z-scores below -1.65 only occur with a 5% probability (one-tailed distribution) and these z-scores can be considered as abnormally low and corresponding to a deficit (Aguert & Capel, 2018).

3 | RESULTS

3.1 | Group-level analyses: Overall differences between groups

Table 2 presents descriptive statistics for the total performance of dyslexic and control children in the various phonological processing and STM tasks. The distribution of all variables was normal or close to normal (the largest skewness coefficient was -1.66, reflecting high overall performance for controls in the phoneme deletion task).

The results of group comparisons (controlling for cognitive ability and vocabulary, and accounting for participant- and item-level variation) are detailed in Table 2. There were significant differences between control and dyslexic participants in all tasks, and all differences remained significant when applying correction for multiple comparisons. In all cases, the dyslexic group performed worse than the control group on average. The results are summarized in Figure 1.

3.2 | Group-level analyses: Group differences controlling for other abilities

The next set of analyses compared the extent of deficits in the dyslexic group across pairs of comparable tasks contrasting the critical variables manipulated in this study (phonological abilities vs. short-term; short-term memory for item information vs. short-term memory for order information). The results of these comparisons are summarized in Table 3.

First, we investigated whether the phonological deficit of dyslexic children was more pronounced, when a high short-term memory load was involved as in the phoneme deletion task » (Minimal pair discrimination vs. phoneme deletion). There was a significant two-way interaction between group and task for the two phonological processing

TABLE 2 Descriptive statistics and group differences between control and dyslexic children.

Measure	Descriptive statistics		Test of the group effect, controlling for cognitive ability and vocabulary		
	Controls *M* (*SD*)	Dyslexics *M* (*SD*)	$\chi^2(1)$	*p*-value	FDR correction
Minimal pair discrimination	0.98 (0.14)	0.95 (0.22)	7.21	0.007	**
Phoneme deletion	0.96 (0.20)	0.88 (0.32)	11.63	<0.001	***
Item delayed repetition	0.61 (0.49)	0.36 (0.48)	13.09	<0.001	***
ISR words—item	0.88 (0.21)	0.80 (0.26)	12.50	<0.001	***
ISR words—serial order	0.83 (0.27)	0.71 (0.35)	17.49	<0.001	***
ISR pseudowords—item	0.60 (0.33)	0.48 (0.34)	15.70	<0.001	***
ISR pseudowords—serial order	0.59 (0.34)	0.44 (0.38)	20.29	<0.001	***
Verbal serial order reconstruction	0.84 (0.24)	0.69 (0.31)	17.22	<0.001	***
Non-verbal serial order reconstruction	0.76 (0.28)	0.60 (0.32)	18.01	<0.001	***

Note: All tasks were scored as average proportion correct for this table.
*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

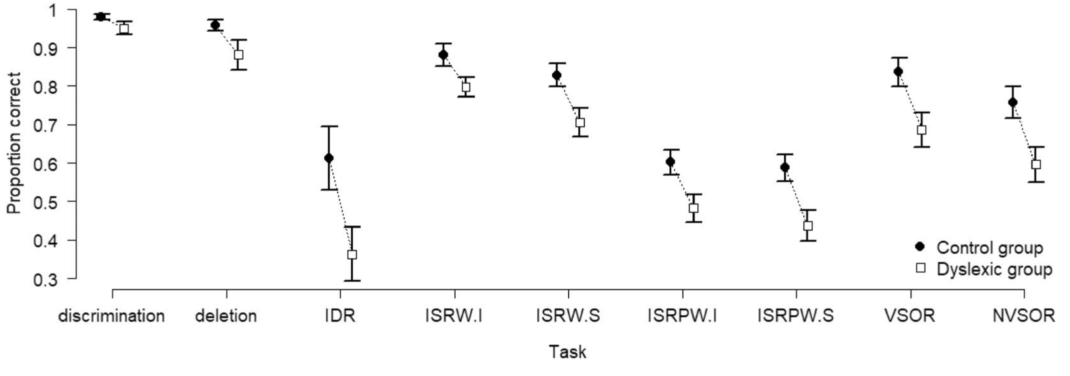

FIGURE 1 Average performance in the two groups for all tasks. Error bars represent 95% confidence intervals of the mean. IDR, Item delayed recall; ISRPW.I, item serial recall for pseudowords, item score; ISRPW.S, item serial recall for pseudowords, serial order score; ISRW.I, item serial recall for words, item score; ISRW.S, item serial recall for words, serial order score; NVSOR, non-verbal serial order reconstruction; VSOR, verbal serial order reconstruction.

tasks, indicating that the dyslexic group was comparatively more impaired on the deletion task than on the minimal pair discrimination task. Second, we explored whether dyslexic children had greater impairment in recalling items in correct order versus recalling items independently of serial order requirements (ISR words—item score vs. serial order score and ISR pseudowords—item score vs. serial order score). The interaction was also significant for the comparison between item scores and serial orders scores on the ISR task for both words and pseudowords, indicating that the dyslexic group was comparatively more impaired for serial order scores (i.e., when taking into account both item recall and serial order recall). We then examined whether the serial order STM deficit was greater than the item STM deficit (Item delayed repetition vs. verbal serial order reconstruction). Finally, we investigated whether the serial order STM deficit was specific to the verbal modality or whether it generalized to the visual modality (Verbal vs. non-verbal serial order reconstruction). There was no interaction for the comparison between item delayed repetition and verbal serial order reconstruction, or for the comparison between the verbal and non-verbal serial order reconstruction tasks.

TABLE 3 Descriptive statistics and group differences between control and dyslexic children.

	Test of the group* task interaction			
Comparison	***F*(1, 51)**	***p*-value**	**FDR correction**	η^2_p
Minimal pair discrimination versus phoneme deletion	6.71	0.012	*	0.12
ISR words—item score versus serial order score	6.12	0.017	*	0.11
ISR pseudowords—item score versus serial order score	10.95	0.006	*	0.18
Item delayed repetition versus verbal serial order reconstruction	2.57	0.115		0.05
Verbal versus nonverbal serial order reconstruction	0.20	0.653		0.00

Abbreviations: FDR, level of significance after applying the correction for false discovery rate; ISR, immediate serial recall.
*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

Next, we assessed the specificity of the deficits of dyslexic children observed in the initial group analyses. First, we tested whether the deficit in STM for serial order was independent of the deficit in STM for items. This was examined based on the item delayed repetition task and the two serial order reconstruction tasks, which maximally oppose item and serial order requirements (rather than the ISR tasks, where participants are required to remember both the items and their serial order). To determine if the deficit in verbal item recall could be explained by the deficit in serial order recall, the effect of group on item delayed repetition task was tested controlling for verbal serial order reconstruction. Second, to test if the deficit in verbal serial order recall could be explained by the deficit in verbal item recall, the effect of group on verbal serial order reconstruction was tested controlling for item delayed repetition task. Next, we examined whether the poor performance of the dyslexic group for the verbal and visual reconstruction tasks reflected a common deficit, after accounting for modality effects. The effect of group on verbal serial order reconstruction was tested controlling for performance in the visual serial order reconstruction task and the item delayed repetition task (the latter for accounting for the verbal aspect of the verbal serial order reconstruction task).

The results of these analyses are summarized in Table 4. Overall, the deficit in verbal item recall appeared to be independent from the deficit in serial order recall: the difference between the two groups in the item delayed repetition task remained significant when controlling for verbal serial order reconstruction. Moreover, the deficit in verbal serial recall remained significant when controlling for the item delayed repetition task, but it became nonsignificant when further adding the visual serial order reconstruction task, suggesting the dependency of the group effect for the visual and verbal serial order reconstruction tasks. A second aspect of this question was to determine whether the deficits in phonological processing and verbal item STM could be explained by each other (such that dyslexic children perform lower in phonological processing because they have difficulties maintaining to-be-processed phonemes in short-term memory, or such that dyslexic children perform lower in verbal item STM because they have difficulties processing to-be-remembered phonemes).

This was tested by considering the two phonological processing tasks, and the two item STM tasks with the highest phonological requirements: item delayed repetition and the item recall score for pseudowords ISR. The effect of group on each of the phonological processing tasks was tested controlling for the two item memory tasks, and the effect of group on each of the item memory tasks was tested controlling for the two phonological processing tasks.

The results are summarized in Table 5. Overall, the effect of group on each of the two phonological processing tasks became non-significant when controlling for performance in verbal item recall, suggesting that poor performance in the phonological tasks could be the consequence of a deficit in verbal STM in dyslexic children. By contrast, the effect of group on the two-item STM tasks remained significant when controlling for phonological processing, indicating that difficulties with phonological processing did not account for the deficit in STM for verbal items.

TABLE 4 Group effect analysis for the verbal item and serial order STM measures.

Dependent variable	Covariates	Test of the effect of group $\chi^2(1)$	*p*-value
Item delayed repetition	Verbal serial order reconstruction	6.55	0.010
Item delayed repetition	Nonverbal serial order reconstruction	7.77	0.005
Item delayed repetition	Verbal serial order reconstruction Nonverbal serial order reconstruction	5.48	0.019
Verbal serial order reconstruction	Item delayed repetition	9.86	0.002
Verbal serial order reconstruction	Nonverbal serial order reconstruction	5.28	0.022
Verbal serial order reconstruction	Item delayed repetition Nonverbal serial order reconstruction	2.46	0.116

TABLE 5 Group effect analysis for the phonological processing and verbal item STM measures.

Dependent variable	Covariates	Test of the effect of group $\chi^2(1)$	*p*-value
Minimal pair discrimination	Item delayed repetition ISR pseudowords—item score	0.39	0.535
Phoneme deletion	Item delayed repetition ISR pseudowords—item score	0.40	0.525
Item delayed repetition	Minimal pair discrimination Phoneme deletion	4.19	0.041
ISR pseudowords—item score	Minimal pair discrimination Phoneme deletion	4.06	0.044

3.3 | Single-subject analyses

Next, we assessed the potential heterogeneity of STM deficits in our group of dyslexic children, by determining, via an individual-level analysis, the distribution of item and serial order STM deficits across our sample. For each child with dyslexia, we computed composite z-scores as described in the Data Analysis section, one for item STM (by averaging the age-corrected z-scores for the item delayed repetition task as well as the word and nonword ISR item recall scores) and one for STM for serial order (by averaging the age-corrected z-scores for the verbal serial order reconstruction and the visual serial order reconstruction tasks). For phonological processing, a composite z-score was determined separately for phonetic perception (minimal pair discrimination task) and phoneme manipulation (on the phoneme deletion task). The phonetic perception composite z-score was computed by averaging the age-corrected z-scores for the standard speech rate score and the accelerated speech rate scores in the minimal pair discrimination task. The phoneme manipulation composite z-score was the average of age-corrected z-scores for the bi-syllabic score, the monosyllabic C-V-C score and the monosyllabic C-C-V score in the phoneme deletion task.

For the STM abilities, composite z-score analysis showed that a total of 13 dyslexic children (52% of the sample) were impaired on at least one STM composite z-score as shown in Table 6. Furthermore, a more detailed analysis reveals three different profiles in the dyslexic group. As shown in Figure 2, four children showed selective item STM impairment E, K, P, R (see Table 2). Six children showed selective serial order STM impairment, C, L, M, V, X, Y. Further three dyslexic children (Q, U, W) showed impairment for both serial order and item STM components. Notably, 12 children showed no impairment as defined by our threshold (composite z-score <-1.65) but their z-scores remained nevertheless negative, indicating overall lower performance as compared to the control group.

For phonological processing, z-score analysis showed that a total of 12 dyslexic children (48% of the sample) were impaired on at least one z-score.

As shown in Figure 3, phonetic discrimination was selectively impaired in three dyslexic children (C, F, O). Phonological awareness was impaired without phonetic discrimination in four children (D, G, K, P). Five dyslexic children showed impairment for both phonetic discrimination and phonological awareness (E, Q, U, V, W).

Finally, we compared composite z-scores between STM and phonological processing domains. On the one hand, the three children (U, Q, W) who had a combined item-serial order deficit in STM also had a double deficit in phonological processing. Of the six children with a serial STM deficit, only one child had a phonetic perception deficit (C) and another had a phonological impairment on both measures (V). Of the four children with an isolated deficit in verbal item STM, three of them had phonological deficits (E, K, P) with, respectively, a double deficit (E) and a phonological awareness disorder (K, P). Overall, children presenting an item STM deficit (isolated or in combination with a serial order STM deficit) also presented a phonological deficit, except for one child (R). Similarly, of the nine dyslexic children with a phonetic perception impairment, only two (F, O) presented a discrimination deficit without a deficit

TABLE 6 Composite z-scores for STM and phonological variables.

Dyslexic child	Item STM composite z-score	Serial order STM composite z-score	Phonetic perception composite z-score	Phonological awareness composite z-score
A	−1.23	−0.91	−1.64	−0.71
B	−0.03	−1.35	0.75	0.85
C	−1.39	−2.89*	−1.68*	−1.42
D	−0.41	−0.75	0.71	−2.45*
E	−1.94*	−0.71	−2.13*	−8.52*
F	−0.67	−0.85	−1.67*	−0.43
G	−0.39	−0.98	0.20	−2.86*
H	−1.33	−0.87	0.69	0.07
I	−0.49	−0.51	−0.30	0.07
J	−1.58	−0.91	0.20	−0.98
K	−1.79*	−1.48	−0.30	−3.08*
L	−1.04	−3.57*	−0.24	0.27
M	−0.96	−1.72*	−0.81	0.25
N	−0.88	−0.88	0.17	0.49
O	−0.04	0.38	−5.06*	−1.09
P	−2.27*	−1.33	0.16	−1.67*
Q	−1.81*	−1.81*	−1.81*	−3.50*
R	−1.70*	−1.02	−0.34	−1.19
S	0.07	−0.78	0.14	−0.71
T	−1.08	−0.26	0.62	0.07
U	−1.90*	−3.34*	−4.04*	−8.07*
V	−1.05	−3.18*	−2.70*	−1.82*
W	−1.75*	−2.27*	−5.10*	−2.86*
X	−1.35	−2.83*	0.62	0.31
Y	−1.53	−3.75*	−0.30	−0.75

*The z-score indicating significant impairment.

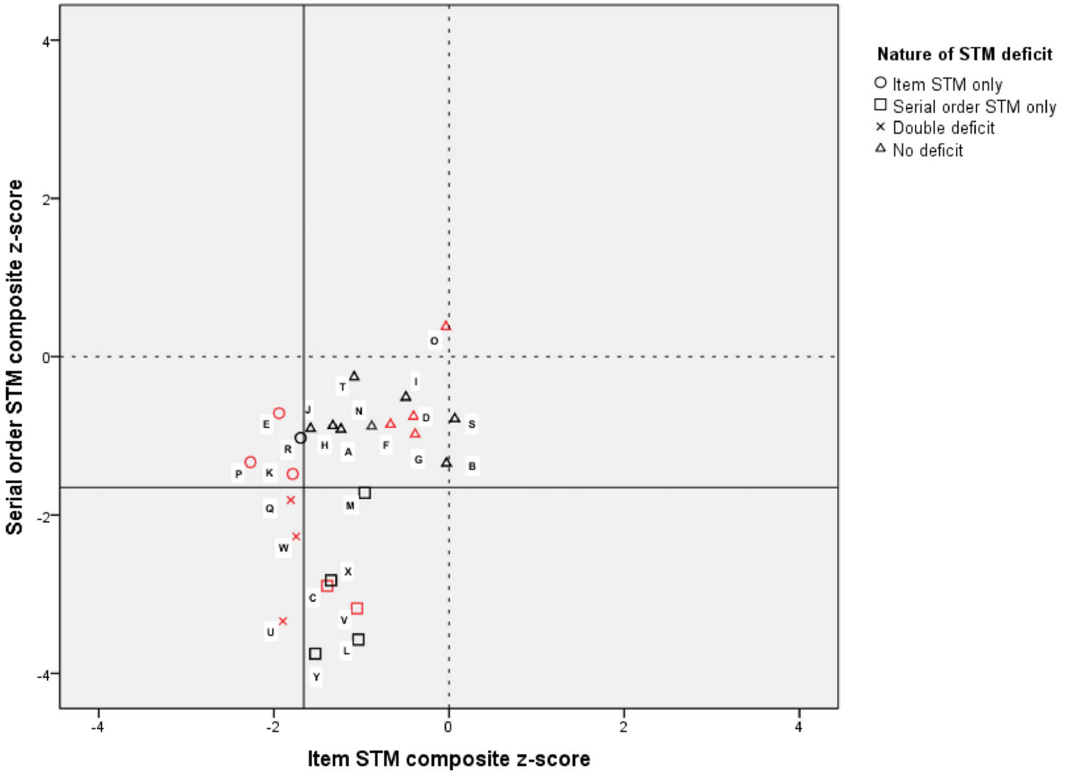

FIGURE 2 Distribution of dyslexic children according to their STM deficits. Lines correspond to z = −1.65 threshold. The red shapes represent dyslexic children with a deficit in at least one component of phonological abilities.

in STM. Similalrly, of the nine dyslexic children with a phonological awareness deficit, phonological awareness was the only deficit in only two dyslexic children (D, G).

4 | DISCUSSION

This study aimed to re-examine item and serial order STM as well as phonological processing abilities in children with dyslexia and to determine the potential heterogeneity of STM deficits in this population. At the group level, deficits in phonological processing as well as in both serial order and item STM were found, in line with previous studies. At the individual level, important heterogeneity of STM deficits was observed with a dissociation between item and serial order STM impairments. Indeed, 24% of children had a selective deficit in serial order STM, and 16% had a selective deficit in item STM, while 12% were impaired on both serial order and item STM. The other children showed STM z-scores that were all below zero except for two children. Our results overall highlight two subgroups of dyslexic children, one subgroup with combined phonological and item STM deficits and another subgroup with more selective serial order STM deficits.

4.1 | The nature of short-term memory deficits in dyslexia

Our group analyses showed poorer STM performance in the dyslexic group relative to the control group, and this was for both item STM and serial order STM. The analyses of covariance showed that the deficit in serial order STM

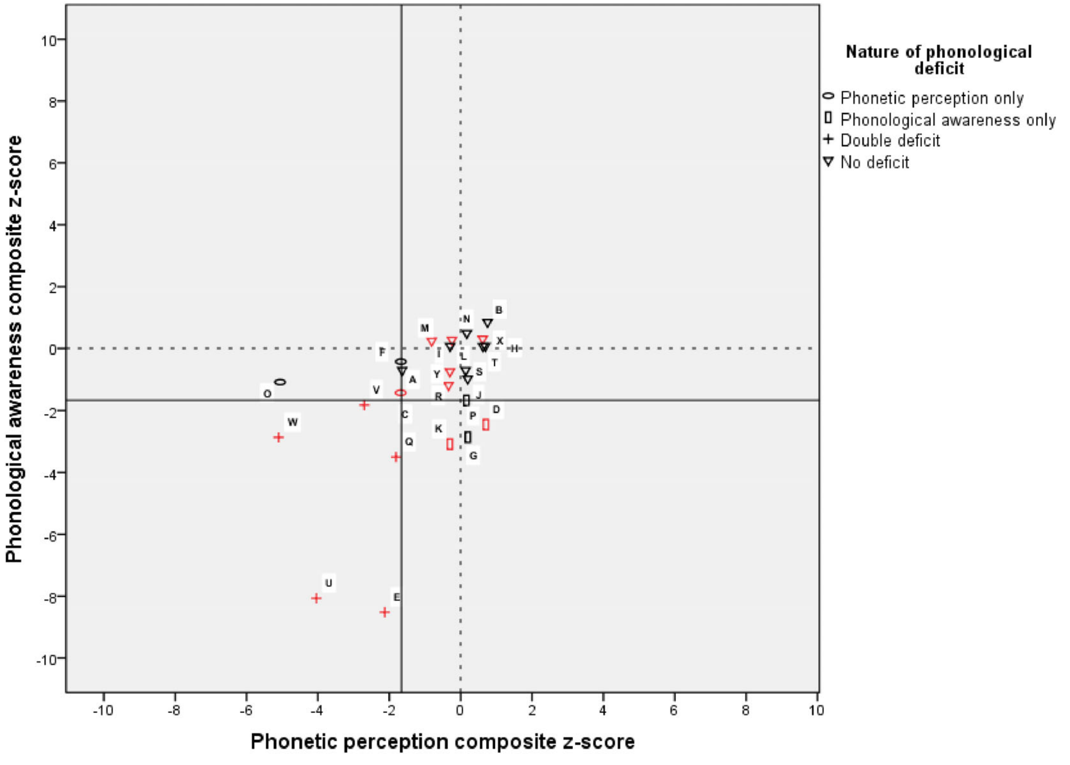

FIGURE 3 Distribution of dyslexic children according to their phonological deficits. Lines correspond to $z = -1.65$ threshold. The red shapes represent dyslexic children with a deficit in at least one STM component.

remained significant after control of group differences in item STM. Furthermore, our children with dyslexia presented a serial order STM deficit in both the verbal and the visual modality. These results are in line with previous studies having explored item and serial order STM abilities in dyslexia (Cowan et al., 2017; Hachmann et al., 2014, 2020; Martinez Perez et al., 2013; Martinez Perez et al., 2015; Martinez Perez, Majerus, Mahot, & Poncelet, 2012; Martinez Perez, Majerus, & Poncelet, 2012; Romani et al., 2015).

Giorgetti and Lorusso (2019) suggested that the serial order STM deficits in dyslexia may be the result of less efficient verbal recoding. Our results are not consistent with this hypothesis, since dyslexic children also performed worse than the control group in the nonverbal serial order reconstruction task including visual presentation of difficult to verbalize nonsense drawings. A potential limitation of our study is that there was an additional oral-to-written mapping process during response production in the serial order reconstruction task. However, the presentation of written cues was intented to facilitate item processing, as it will give full access to the items that had been presented and only their serial order needs to be reconstructed. Furthermore, recognition of written digits is a highly overlearnt process even in dyslexic children although we cannot rule out that dyslexic children may be slower in naming digits (e.g., Nicolson & Fawcett, 1994). In order to neutralize any bias that may result at this level, we used several, structurally different tasks to obtain composite serial order versus item STM abilities. Note also that the other serial order STM tasks did not include oral-to-written mapping processes and that we observed the same results even for purely visual task conditions (the visual serial order recognition tasks). Hence, although we acknowledge that the oral-to-written mapping of the verbal serial order reconstruction could have led to some slowing of results, we believe that the overall study design allows to minimize the biases that could have resulted from this situation. However, the poor performance of the dyslexic group for the verbal and visual reconstruction tasks appeared to reflect a common deficit, as suggested by analysis of covariance.

Our individual-level analyses also revealed important new findings. First, 52% of the children with dyslexia showed a 'true' deficit on at least one of the two STM components (relative to the deficit-threshold of performance 1.65 standard deviations below control performance), while the remaining children showed STM z-scores that were all below zero except for two children. Second, we observed a heterogeneity of STM impairment in dyslexic children, with a dissociation between serial order and item STM deficits. Indeed, 24% of children had a selective impairment of serial order STM, and 16% had a selective impairment of item STM. 12% of children were impaired on both serial order and item STM. Third, we observed that the serial order STM deficit could be detected in dyslexic children without being systematically associated with an impairment of phonetic discrimination or phonological awareness. Indeed, of the six children with a serial order STM deficit, only one child had a phonetic discrimination deficit and another had a phonological impairment on both measures.

These individual profile analyses complete the results of the group analyses and support the idea that the item and serial order STM deficits are independent. These dissociations are consistent with longitudinal studies which have shown that serial order STM abilities predict reading acquisition independently of item STM abilities (Binamé & Poncelet, 2016; Hachmann et al., 2020; Martinez Perez, Majerus, & Poncelet, 2012; Ordonez Magro et al., 2020; Schraeyen et al., 2017). More generally, several studies have shown that dyslexic individuals may have deficits in sequential information processing also in tasks outside the STM domain (Hedenius et al., 2013; Peter et al., 2018, 2021; Ram-Tsur et al., 2006, 2008). Importantly, the present study suggests that if this is the case, it does not concern all children with dyslexia to the same extent. However, an alternative hypothesis is to consider that these dissociations between serial order STM deficits and phonological processing impairments are only a consequence of a difference in material and procedure. Indeed, part of the item measures we used were very similar to the phonological processing tasks because they used pseudowords. Hence it could be argued that the closer association between item STM tasks and phonological processing tasks, relative to serial order STM tasks is due to stimulus material similarity rather than item STM per se. Critically, whether running the analyses on the item versus serial order scores for the immediate serial recall tasks sharing the same material or on the item delayed repetition versus serial order reconstruction tasks that use different material, the same pattern of results was observed. Furthermore, while using the same material, the item STM task predicted phonological processing abilities but the reverse was not true.

4.2 | Are verbal item STM deficits independent of phonological impairment?

Our group analyses showed poorer phonological processing performance in the dyslexic group relative to the control group for both phonetic discrimination and phonological awareness tasks, and the group effect was more pronounced for the phonological awareness measures. These results are consistent with previous studies showing a deficit in phonological processing (Soroli et al., 2010).

Our analysis of individual profiles revealed that 48% of the children with dyslexia showed a deficit on at least one of the two phonological processing tasks. As in the case of STM abilities, we observed a large heterogeneity in phonological processing abilities, with 12% of dyslexic children presenting an impairment of phonetic discrimination without phonological awareness deficit, 16% presenting an impairment of phonological awareness without phonetic discrimination deficit and 20% showing an impairment for both phonemic discrimination and phonological awareness. In addition, we observed a frequent association between phonetic discrimination impairment and impairment of either item STM or phonological awareness. Indeed, of the eight dyslexic children with an impairment of phonetic perception, only two had a z-score above the deficit threshold in verbal item STM or phonological awareness.

Furthermore, when we controlled for group differences in either the phonological awareness task or the phonetic discrimination task, the group differences in the verbal STM tasks remained significant. At the same time, the group differences in the phonemic deletion task and phonetic discrimination task disappeared after control of group differences in the verbal STM tasks. This suggests that in children with dyslexia, verbal item STM deficits are not only the consequence of phonological awareness or phonetic discrimination impairments. But poor performance in the phonological processing tasks may be accounted for by item STM impairment. Our results contrast with the hypothesis that phonological awareness deficits would be the only origin of low performance in verbal STM tasks (Jarrold et al., 2009; Messbauer & de Jong, 2003; Snowling et al., 1991; Windfuhr & Snowling, 2001). However, it is also possible that our item STM tasks were more sensitive than the two phonological tasks, as is suggested by the larger inter-individual variability for the STM scores as compared to the phonological scores. Soroli et al. (2010) showed that dyslexic adults had difficulties in phonological processing particularly when the working memory load of the task was high. Overall, when considering together the results of the group-level and individual-level analyses, the safest conclusion is that item STM and phonological processing impairment are associated rather than dissociated. In addition, it is likely that phonological awareness tasks involve STM loading at the sequential level, particularly in young children whose phonological segmentation skills are less developed/automated. Our multiple case studies and our additional analyses in the appendix (Table A1) suggest that the deficit of dyslexic children in the phonological awareness task is not merely associated with low automated phonological segmentation skills and the sequential aspects of this task.

4.3 | Are there several possible pathways leading to dyslexia?

The present study appears to highlight at least two distinct profiles of STM deficits in dyslexia, one profile involving children with combined phonological and item STM deficits and another profile with more specific serial order STM deficits. This finding is in line with other recent and less recent studies that have suggested the existence of several pathways that may lead to dyslexia. Pennington et al. (2012) tested five different pathways to dyslexia including two single-deficit models (single phonological deficit; single deficit subtypes), two multiple-deficit models (phonological core with multiple deficits; multiple deficits) and one hybrid model that encompassed all four previous possibilities. The cognitive abilities measured in that study were phonological awareness, language skills and processing speed and/or naming speed in two large samples of children. The authors found that although 40% of the dyslexic cases of these samples did not show deficits consistent with the different models, the hybrid model provided the best global fit to the data. This indicates that there are several possible pathways for developing dyslexia, some involving single deficits and others involving multiple deficits. In addition, although the phonological deficit hypothesis remains among the most influential in dyslexia research, phonological problems may need to interact with other cognitive risk factors to eventually lead to reading disability (Peterson & Pennington, 2012).

A further question that arises is whether the phonological-item STM and serial order STM pathways could lead to different reading profiles in dyslexia. Nithart et al. (2011) observed that serial order STM was predictive of the development of early reading decoding abilities, while phonological STM predicted word recognition performance. For these authors, the practice of grapheme-phoneme conversion rules would be related to serial STM capabilities involved in maintaining the order of phoneme sequences during decoding, while phonological STM would be involved in associating an assembled sequence of phonemes to long-term phonological representations of words during written word recognition. Martinez Perez, Majerus, and Poncelet (2012), conducted a longitudinal study with children from kindergarten to first grade, and observed that order STM ability but not item STM ability, predicted independent variance in reading decoding performance 1 year later. They also argued for a specific role of order STM in the acquisition of decoding. Hachmann et al. (2020) provided further data highlighting serial order STM as an important factor in the early development of reading abilities, particularly during decoding and grapheme-phoneme conversion. In the light of these findings, we suggest that dyslexic children with an item STM deficit may present increased difficulties in phonological coding, defined by Leinenger (2014) as the recoding of written, orthographic information into a sound-based code. In contrast, dyslexic children with a serial order STM deficit may be most impaired for sequential decoding in reading, when the successive products of letter-sound conversion processes must be stored in a sequential manner before reading output (Martinez Perez, Majerus, & Poncelet, 2012).

This hypothesis is also supported by data from spelling acquisition. Biname and Poncelet (2016) observed that serial order STM ability was a solid independent predictor of nonword reading and spelling performance at first and second grades, but was not related to frequent and irregular word reading and spelling abilities. These findings support the hypothesis that serial order STM does not directly contribute to reading and spelling when orthographic representations in long-term memory can be used for reading or spelling words. Ordonez Magro et al. (2020, 2021) showed that serial order STM abilities remained, however, predictive of reading and spelling abilities of both regular and irregular words for children in the second grade of elementary school, likely because the nonlexical reading procedure is still used as orthographic representations are not yet fully represented in long-term memory. It is therefore likely that the involvement of serial order STM in reading performance is modulated by the quality and quantity of orthographic representations stored in long-term memory. In sum, the developmental trajectory of dyslexic children may differ, depending in part on the nature of their STM deficit. Dyslexic children with an item STM deficit may present difficulties in both the lexical and nonlexical reading procedures, in association with phonological impairment, and may thus benefit from early interventions based on training phonological skills. On the other hand, dyslexic children with a serial order STM deficit may benefit more from interventions based on the installation of long-term orthographic representation in order to increase reliance on the lexical reading procedure, thereby compensating for their sequential processing and decoding difficulties.

5 | CONCLUSION

This study examined phonological processing, item STM and serial order STM abilities in children with dyslexia, and confirmed dissociations between item STM/phonological deficits versus serial order STM deficits, at both group-level and individual-level analyses. Our results highlight the interest for practitioners to consider reading as a learning process involving both language and nonlanguage cognitive abilities, which can be impaired in distinct ways. This study also stresses the importance of conducting comprehensive STM assessments for individuals with reading disabilities in order to allow for the implementation of the most adapted remediation procedure.

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CONFLICT OF INTEREST STATEMENT

We have no known conflicts of interest to declare.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

Abdel-Khalek, A. M. (2005). Reliability and factorial validity of the standard progressive matrices among Kuwaiti children ages 8 to 15 years. *Perceptual and Motor Skills*, *101*(2), 409–412.

Abrahamse, E., van Dijck, J.-P., Majerus, S., & Fias, W. (2014). Finding the answer in space: The mental whiteboard hypothesis on serial order in working memory. *Frontiers in Human Neuroscience*, *8*, 1–12. https://doi.org/10.3389/fnhum.2014.00932

Aguert, M., & Capel, A. (2018). Mieux comprendre les scores z pour bien les utiliser. *Rééducation Orthophonique*, *274*, 61–85.

Attout, L., Ordonez, L., Arnaud, M., & Majerus, S. (2018). *The developmental neural substrates of item and serial order components of verbal working memory*. *October*, 1–13. https://doi.org/10.1002/hbm.24466

Attout, L., Ordonez Magro, L., Szmalec, A., & Majerus, S. (2019). The developmental neural substrates of item and serial order components of verbal working memory. *Human Brain Mapping*, *40*(5), 1541–1553. https://doi.org/10.1002/hbm.24466

Attout, L., van der Kaa, M.-A., George, M., & Majerus, S. (2012). Dissociating short-term memory and language impairment: The importance of item and serial order information. *Aphasiology*, *26*(3–4), 355–382. https://doi.org/10.1080/02687038.2011.604303

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01

Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society: Series B: Methodological*, *57*(1), 289–300. https://doi.org/10.1111/j.2517-6161.1995.tb02031.x

Berninger, V. W., Abbott, R. D., Thomson, J., Wagner, R., Swanson, H. L., Wijsman, E. M., & Raskind, W. (2009). Modeling phonological Core deficits within a working memory architecture in children and adults with developmental dyslexia. *Scientific Studies of Reading*, *10*(2), 165–198. https://doi.org/10.1207/s1532799xssr1002_3

Binamé, F., & Poncelet, M. (2016). Order short-term memory capacity predicts nonword reading and spelling in first and second grade. *Reading and Writing*, *29*(1), 1–20. https://doi.org/10.1007/s11145-015-9577-9

Bonin, P., Méot, A., Ferrand, L., & Roux, S. (2011). L'imageabilité : Normes et relations avec d'autres variables psycholinguistiques. *L'Année Psychologique*, *111*(02), 327–357. https://doi.org/10.4074/S0003503311002041

Burgess, N., & Hitch, G. J. (1999). Memory for serial order: A network model of the phonological loop and its timing. *Psychological Review*, *106*(3), 551–581. https://doi.org/10.1037/0033-295X.106.3.551

Burgess, N., & Hitch, G. J. (2006). A revised model of short-term memory and long-term learning of verbal sequences. *Journal of Memory and Language*, *55*(4), 627–652. https://doi.org/10.1016/j.jml.2006.08.005

Catts, H. W., Adlof, S. M., Hogan, T. P., & Weismer, S. E. (2005). Are specific language impairment and dyslexia distinct disorders? *Journal of Speech, Language, and Hearing Research*, *48*(6), 1378–1396. https://doi.org/10.1044/1092-4388(2005/096)

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: Serial order memory in dyslexia. *Dyslexia*, *23*(3), 209–233. https://doi.org/10.1002/dys.1557

Crawford, J. R., & Howell, D. C. (1998). Comparing an individual's test score against norms derived from small samples. *The Clinical Neuropsychologist*, *12*(4), 482–486. https://doi.org/10.1076/clin.12.4.482.7241

De Groot, B. J. A., van den Bos, K. P., van der Meulen, B. F., & Minnaert, A. E. M. G. (2015). Rapid naming and phonemic awareness in children with Reading disabilities and/or specific language impairment: Differentiating processes? *Journal of Speech, Language, and Hearing Research*, *58*(5), 1538–1548. https://doi.org/10.1044/2015_JSLHR-L-14-0019

Dunn, L., Theriault-Whalen, C., & Dunn, M. (1993). *Echelle de vocabulaire en images Peabody*. ATM.

Gathercole, S. E., Alloway, T. P., Willis, C., & Adams, A.-M. (2006). Working memory in children with reading disabilities. *Journal of Experimental Child Psychology*, *93*(3), 265–281. https://doi.org/10.1016/j.jecp.2005.08.003

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

Giorgetti, M., & Lorusso, M. L. (2019). Specific conditions for a selective deficit in memory for order in children with dyslexia. *Child Neuropsychology*, *25*(6), 742–771. https://doi.org/10.1080/09297049.2018.1530746

Gombert, J. E. (1992). *Metalinguistic development*. Harvester Wheatsheaf.

Hachmann, W. M., Bogaerts, L., Szmalec, A., Woumans, E., Duyck, W., & Job, R. (2014). Short-term memory for order but not for item information is impaired in developmental dyslexia. *Annals of Dyslexia*, *64*(2), 121–136. https://doi.org/10.1007/s11881-013-0089-5

Hachmann, W. M., Cashdollar, N., Postiglione, F., & Job, R. (2020). The relationship of domain-general serial order memory and reading ability in school children with and without dyslexia. *Journal of Experimental Child Psychology*, *193*, 104789. https://doi.org/10.1016/j.jecp.2019.104789

Hedenius, M., Persson, J., Alm, P. A., Ullman, M. T., Howard, J. H., Howard, D. V., & Jennische, M. (2013). Impaired implicit sequence learning in children with developmental dyslexia. *Research in Developmental Disabilities*, *34*(11), 3924–3935. https://doi.org/10.1016/j.ridd.2013.08.014

Hulme, C., Maughan, S., & Brown, G. (1991). Memory for familiar and unfamiliar words: Evidence for a long-term memory contribution to short-term memory span. *Journal of Memory and Language*, *30*, 685–701.

Institut national de la statistique et des études économiques (INSEE). (2020). Nomenclatures des professions et catégories socioprofessionnelles. https://www.insee.fr/fr/information/2406153

Jarrold, C., Thorn, A. S. C., & Stephens, E. (2009). The relationships among verbal short-term memory, phonological awareness, and new word learning: Evidence from typical development and down syndrome. *Journal of Experimental Child Psychology*, *102*(2), 196–218. https://doi.org/10.1016/j.jecp.2008.07.001

Jeffries, S., & Everatt, J. (2004). Working memory: Its role in dyslexia and other specific learning difficulties. *Dyslexia (Chichester, England)*, *10*(3), 196–214. https://doi.org/10.1002/dys.278

Kalm, K., & Norris, D. (2014). The representation of order information in auditory-verbal short-term memory. *Journal of Neuroscience*, *34*(20), 6879–6886. https://doi.org/10.1523/JNEUROSCI.4104-13.2014

Kibby, M. Y. (2009). There are multiple contributors to the verbal short-term memory deficit in children with developmental Reading disabilities. *Child Neuropsychology*, *15*(5), 485–506. https://doi.org/10.1080/09297040902748218

Laasonen, M., Virsu, V., Oinonen, S., Sandbacka, M., Salakari, A., & Service, E. (2012). Phonological and sensory short-term memory are correlates and both affected in developmental dyslexia. *Reading and Writing*, *25*(9), 2247–2273. https://doi.org/10.1007/s11145-011-9356-1

Le Jan, G., Le Bouquin-Jeannès, R., Costet, N., Trolès, N., Scalart, P., Pichancourt, D., Faucon, G., & Gombert, J.-E. (2011). Multivariate predictive model for dyslexia diagnosis. *Annals of Dyslexia*, *61*(1), 1–20. https://doi.org/10.1007/s11881-010-0038-5

Leclercq, A.-L., & Majerus, S. (2010). Serial-order short-term memory predicts vocabulary development: Evidence from a longitudinal study. *Developmental Psychology*, *46*(2), 417–427. https://doi.org/10.1037/a0018540

Lefavrais, P. (2005). *Test de leximétrie de l'Alouette* (ECPA).

Leinenger, M. (2014). Phonological coding during reading. *Psychological Bulletin*, *140*(6), 1534–1555. https://doi.org/10.1037/a0037830

Lenhard, A., Lenhard, W., & Gary, S. (2019). Continuous norming of psychometric tests: A simulation study of parametric and semi-parametric approaches. *PLoS One*, *14*(9), 1–30. https://doi.org/10.1371/journal.pone.0222279

Loucas, T., Baird, G., Simonoff, E., & Slonims, V. (2016). Phonological processing in children with specific language impairment with and without reading difficulties: Phonological processing, language impairment and reading. *International Journal of Language & Communication Disorders*, *51*(5), 581–588. https://doi.org/10.1111/1460-6984.12225

Majerus, S. (2009). Verbal short-term memory and temporary activation of language representations: The importance of distinguishing item and order information. In A. S. Thorn & M. P. A. Page (Eds.), *Interactions between short-term and long-term memory in the verbal domain* (pp. 244–276). Psychology Press.

Majerus, S., & Boukebza, C. (2013). Short-term memory for serial order supports vocabulary development: New evidence from a novel word learning paradigm. *Journal of Experimental Child Psychology*, *116*, 811–828.

Majerus, S., & Cowan, N. (2016). The nature of verbal short-term impairment in dyslexia: The importance of serial order. *Frontiers in Psychology*, *7*(OCT), 1–8. https://doi.org/10.3389/fpsyg.2016.01522

Majerus, S., D'Argembeau, A., Martinez Perez, T., Belayachi, S., van der Linden, M., Collette, F., Salmon, E., Seurinck, R., Fias, W., & Maquet, P. (2010). The commonality of neural networks for verbal and visual short-term memory. *Journal of Cognitive Neuroscience*, *22*(11), 2570–2593. https://doi.org/10.1162/jocn.2009.21378

Majerus, S., Poncelet, M., Elsen, B., & van der Linden, M. (2006). Exploring the relationship between new word learning and short-term memory for serial order recall, item recall, and item recognition. *European Journal of Cognitive Psychology*, *18*(6), 848–873. https://doi.org/10.1080/09541440500446476

Majerus, S., Poncelet, M., Greffe, C., & van der Linden, M. (2006). Relations between vocabulary development and verbal short-term memory: The relative importance of short-term memory for serial order and item information. *Journal of Experimental Child Psychology*, *93*(2), 95–119. https://doi.org/10.1016/j.jecp.2005.07.005

Majerus, S., Poncelet, M., van der Linden, M., & Weekes, B. (2008). Lexical learning in bilingual adults: The relative importance of short-term memory for serial order and phonological knowledge. *Cognition*, *107*, 395–419.

Majerus, S., van der Kaa, M.-A., Renard, C., van der Linden, M., & Poncelet, M. (2005). Treating verbal short-term memory deficits by increasing the duration of temporary phonological representations: A case study. *Brain and Language*, *95*(1), 174–175. https://doi.org/10.1016/j.bandl.2005.07.094

Marshuetz, C., Smith, E. E., Jonides, J., DeGutis, J., & Chenevert, T. L. (2000). Order information in working memory: FMRI evidence for parietal and prefrontal mechanisms. *Journal of Cognitive Neuroscience*, *12*(Supplement 2), 130–144. https://doi.org/10.1162/08989290051137459

Martinez Perez, T., Majerus, S., Mahot, A., & Poncelet, M. (2012). Evidence for a specific impairment of serial order short-term memory in dyslexic children: Serial order STM deficits in dyslexia. *Dyslexia*, *18*(2), 94–109. https://doi.org/10.1002/dys.1438

Martinez Perez, T., Majerus, S., & Poncelet, M. (2012). The contribution of short-term memory for serial order to early reading acquisition: Evidence from a longitudinal study. *Journal of Experimental Child Psychology*, *111*(4), 708–723. https://doi.org/10.1016/j.jecp.2011.11.007

Martinez Perez, T., Majerus, S., & Poncelet, M. (2013). Impaired short-term memory for order in adults with dyslexia. *Research in Developmental Disabilities*, *34*(7), 2211–2223. https://doi.org/10.1016/j.ridd.2013.04.005

Martinez Perez, T., Poncelet, M., Salmon, E., & Majerus, S. (2015). Functional alterations in order short-term memory networks in adults with dyslexia. *Developmental Neuropsychology*, *40*(7–8), 407–429. https://doi.org/10.1080/87565641.2016.1153098

Mathôt, S., Schreij, D., & Theeuwes, J. (2012). OpenSesame: An open-source, graphical experiment builder for the social sciences. *Behavior Research Methods*, *44*(2), 314–324. https://doi.org/10.3758/s13428-011-0168-7

McArthur, G., & Castles, A. (2013). Phonological processing deficits in specific reading disability and specific language impairment: Same or different? *Journal of Research in Reading*, *36*(3), 280–302. https://doi.org/10.1111/j.1467-9817.2011.01503.x

McArthur, G. M., Hogben, J. H., Edwards, V. T., Heath, S. M., & Mengler, E. D. (2000). On the "specifics" of specific reading disability and specific language impairment. *Journal of Child Psychology and Psychiatry, and Allied Disciplines*, *41*(7), 869–874. https://doi.org/10.1111/1469-7610.00674

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

Messbauer, V. C. S., & de Jong, P. F. (2003). Word, nonword, and visual paired associate learning in Dutch dyslexic children. *Journal of Experimental Child Psychology*, *84*(2), 77–96. https://doi.org/10.1016/S0022-0965(02)00179-0

New, B., Pallier, C., Brysbaert, M., & Ferrand, L. (2004). Lexique 2: A new French lexical database. *Behavior Research Methods, Instruments, & Computers*, *36*(3), 516–524. https://doi.org/10.3758/BF03195598

Nicolson, R. I., & Fawcett, A. J. (1994). Reaction times and dyslexia. *The Quarterly Journal of Experimental Psychology Section A*, *47*(1), 29–48. https://doi.org/10.1080/14640749408401142

Nithart, C., Demont, E., Majerus, S., Leybaert, J., Poncelet, M., & Metz-Lutz, M.-N. (2009). Reading disabilities in SLI and dyslexia result from distinct phonological impairments. *Developmental Neuropsychology*, *34*(3), 296–311. https://doi.org/10.1080/87565640902801841

Nithart, C., Demont, E., Metz-Lutz, M.-N., Majerus, S., Poncelet, M., & Leybaert, J. (2011). Early contribution of phonological awareness and later influence of phonological memory throughout Reading acquisition: PHONOLOGICAL AWARENESS AND MEMORY PREDICT READING ACQUISITION. *Journal of Research in Reading*, *34*(3), 346–363. https://doi.org/10.1111/j.1467-9817.2009.01427.x

Oosterhuis, H. E. M., van der Ark, L. A., & Sijtsma, K. (2016). Sample size requirements for traditional and regression-based norms. *Assessment*, *23*(2), 191–202. https://doi.org/10.1177/1073191115580638

Ordonez Magro, L., Majerus, S., Attout, L., Poncelet, M., Smalle, E. H. M., & Szmalec, A. (2020). The contribution of serial order short-term memory and long-term learning to reading acquisition: A longitudinal study. *Developmental Psychology*, *56*(9), 1671–1683. https://doi.org/10.1037/dev0001043

Ordonez Magro, L., Majerus, S., Attout, L., Poncelet, M., Smalle, E. H. M., & Szmalec, A. (2021). Do serial order short-term memory and long-term learning abilities predict spelling skills in school-age children? *Cognition*, *206*, 104479. https://doi.org/10.1016/j.cognition.2020.104479

Papagno, C., Comi, A., Riva, M., Bizzi, A., Vernice, M., Casarotti, A., Fava, E., & Bello, L. (2017). Mapping the brain network of the phonological loop: The phonological loop brain network. *Human Brain Mapping*, *38*(6), 3011–3024. https://doi.org/10.1002/hbm.23569

Peng, P., Barnes, M., Wang, C., Wang, W., Li, S., Swanson, H. L., Dardick, W., & Tao, S. (2018). A meta-analysis on the relation between reading and working memory. *Psychological Bulletin*, *144*(1), 48–76. https://doi.org/10.1037/bul0000124

Pennington, B. F., Santerre-Lemmon, L., Rosenberg, J., MacDonald, B., Boada, R., Friend, A., Leopold, D. R., Samuelsson, S., Byrne, B., Willcutt, E. G., & Olson, R. K. (2012). Individual prediction of dyslexia by single versus multiple deficit models. *Journal of Abnormal Psychology*, *121*(1), 212–224. https://doi.org/10.1037/a0025823

Peter, B., Albert, A., & Gray, S. (2021). Spelling errors reveal underlying sequential and spatial processing deficits in adults with dyslexia. *Clinical Linguistics & Phonetics*, *35*(4), 310–339. https://doi.org/10.1080/02699206.2020.1780322

Peter, B., Lancaster, H., Vose, C., Middleton, K., & Stoel-Gammon, C. (2018). Sequential processing deficit as a shared persisting biomarker in dyslexia and childhood apraxia of speech. *Clinical Linguistics & Phonetics*, *32*(4), 316–346. https://doi.org/10.1080/02699206.2017.1375560

Peterson, R. L., & Pennington, B. F. (2012). Developmental dyslexia. *The Lancet*, *379*(9830), 1997–2007. https://doi.org/10.1016/S0140-6736(12)60198-6

Peterson, R. L., & Pennington, B. F. (2015). Developmental dyslexia. *Annual Review of Clinical Psychology*, *11*(1), 283–307. https://doi.org/10.1146/annurev-clinpsy-032814-112842

R Core Team. (2022). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Ram-Tsur, R., Faust, M., & Zivotofsky, A. Z. (2006). Sequential processing deficits of reading disabled persons is independent of inter-stimulus interval. *Vision Research*, *46*(22), 3949–3960. https://doi.org/10.1016/j.visres.2006.07.001

Ram-Tsur, R., Faust, M., & Zivotofsky, A. Z. (2008). Poor performance on serial visual tasks in persons with Reading disabilities: Impaired working memory? *Journal of Learning Disabilities*, *41*(5), 437–450. https://doi.org/10.1177/0022219408321141

Ramus, F., Marshall, C. R., Rosen, S., & Van Der Lely, H. K. J. (2013). Phonological deficits in specific language impairment and developmental dyslexia: Towards a multidimensional model. *Brain*, *136*(2), 630–645. https://doi.org/10.1093/brain/aws356

Ramus, F., & Szenkovits, G. (2008). What phonological deficit? *Quarterly Journal of Experimental Psychology*, *61*(1), 129–141. https://doi.org/10.1080/17470210701508822

Raven, J. C., Court, J. H., & Raven, J. (1998). *Colored progressive matrices*. Oxford psychologists press.

Romani, C., Tsouknida, E., & Olson, A. (2015). Encoding order and developmental dyslexia: A family of skills predicting different orthographic components. *Quarterly Journal of Experimental Psychology*, *68*(1), 99–128. https://doi.org/10.1080/17470218.2014.938666

Saint-Aubin, J., & Poirier, M. (1999). Semantic similarity and immediate serial recall: Is there a detrimental effect on order information? *The Quarterly Journal of Experimental Psychology A*, *52*(2), 367–394. https://doi.org/10.1080/027249899391115

Schraeyen, K., Geudens, A., Ghesquière, P., van der Elst, W., & Sandra, D. (2017). Poor performance on the retention of phonemes' serial order in short-term memory reflects young children's poor reading skills. *The Mental Lexicon*, *12*(1), 129–158. https://doi.org/10.1075/ml.12.1.06sch

Schraeyen, K., van der Elst, W., Geudens, A., Ghesquière, P., & Sandra, D. (2019). Short-term memory problems for phonemes' serial order in adults with dyslexia: Evidence from a different analysis of the nonword repetition task. *Applied PsychoLinguistics*, *40*(3), 613–644. https://doi.org/10.1017/S0142716418000759

Snowling, M., Chiat, S., & Hulme, C. (1991). Words, nonwords, and phonological processes: Some comments on Gathercole, Willis, Emslie, and Baddeley. *Applied PsychoLinguistics*, *12*(3), 369–373. https://doi.org/10.1017/S0142716400009279

Soroli, E., Szenkovits, G., & Ramus, F. (2010). Exploring dyslexics' phonological deficit III: Foreign speech perception and production. *Dyslexia (Chichester, England)*, *16*(4), 318–340. https://doi.org/10.1002/dys.415

Spanoudis, G. C., Papadopoulos, T. C., & Spyrou, S. (2019). Specific language impairment and Reading disability: Categorical distinction or continuum? *Journal of Learning Disabilities*, *52*(1), 3–14. https://doi.org/10.1177/0022219418775111

Sprenger-Charolles, L., Colé, P., Béchennec, D., & Kipffer-Piquard, A. (2005). French normative data on reading and related skills from EVALEC, a new computerized battery of tests (end grade 1, grade 2, grade 3, and grade 4). *European Review of Applied Psychology*, *55*(3), 157–186. https://doi.org/10.1016/j.erap.2004.11.002

Staels, E., & Van Den Broeck, W. (2014). Order short-term memory is not impaired in dyslexia and does not affect orthographic learning. *Frontiers in Human Neuroscience*, *8*, 1–16.

Swanson, H. L., Kehler, P., & Jerman, O. (2010). Working memory, strategy knowledge, and strategy instruction in children with Reading disabilities. *Journal of Learning Disabilities*, *43*(1), 24–47. https://doi.org/10.1177/0022219409338743

Swanson, H. L., Zheng, X., & Jerman, O. (2009). Working memory, short-term memory, and Reading disabilities: A selective meta-analysis of the literature. *Journal of Learning Disabilities*, *42*(3), 260–287. https://doi.org/10.1177/0022219409331958

Thomson, J. M., & Goswami, U. (2008). Rhythmic processing in children with developmental dyslexia: Auditory and motor rhythms link to reading and spelling. *Journal of Physiology, Paris*, *102*(1–3), 120–129. https://doi.org/10.1016/j.jphysparis.2008.03.007

Tiffin-Richards, M. C., Hasselhorn, M., Woerner, W., Rothenberger, A., & Banaschewski, T. (2008). Phonological short-term memory and central executive processing in attention-deficit/hyperactivity disorder with/without dyslexia—Evidence of cognitive overlap. *Journal of Neural Transmission (Vienna, Austria: 1996)*, *115*(2), 227–234. https://doi.org/10.1007/s00702-007-0816-3

Tubach, J. L., & Boë, L. J. (1990). *Un corpus de transcription phonétique*. Telecom.

van Breukelen, G. J. P., & Vlaeyen, J. W. S. (2005). Norming clinical questionnaires with multiple regression: The pain cognition list. *Psychological Assessment*, *17*(3), 336–344. https://doi.org/10.1037/1040-3590.17.3.336

van Dijck, J.-P., Abrahamse, E. L., Majerus, S., & Fias, W. (2013). Spatial attention interacts with serial-order retrieval from verbal working memory. *Psychological Science*, *24*(9), 1854–1859. https://doi.org/10.1177/0956797613479610

Wang, S., & Gathercole, S. E. (2013). Working memory deficits in children with reading difficulties: Memory span and dual task coordination. *Journal of Experimental Child Psychology*, *115*(1), 188–197. https://doi.org/10.1016/j.jecp.2012.11.015

Wang, X., Xuan, Y., & Jarrold, C. (2016). Using a process dissociation approach to assess verbal short-term memory for item and order information in a sample of individuals with a self-reported diagnosis of dyslexia. *Frontiers in Psychology*, *7*, 1–10. https://doi.org/10.3389/fpsyg.2016.00208

Windfuhr, K. L., & Snowling, M. J. (2001). The relationship between paired associate learning and phonological skills in normally developing readers. *Journal of Experimental Child Psychology*, *80*(2), 160–173. https://doi.org/10.1006/jecp.2000.2625

Zachary, R. A., & Gorsuch, R. L. (1985). Continuous norming: Implications for the WAIS-R. *Journal of Clinical Psychology*, *41*(1), 86–94. https://doi.org/10.1002/1097-4679(198501)41:1<86::AID-JCLP2270410115>3.0.CO;2-W

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APPENDIX A

TABLE A1 Descriptive statistics and group differences between control and dyslexic children in phoneme deletion task by distinguishing the segmentation levels of the pseudowords

	Descriptive statistics		Test of the effect of group	
	Controls	Dyslexics		
Measure	*M* (*SD*)	*M* (*SD*)	$\chi^2(1)$	*p*-value
Tri-syllabic pseudowords	0.99 (0.08)	0.95 (0.20)	4.59	0.032
C-V-C pseudowords	0.99 (0.07)	0.94 (0.23)	7.89	0.005
C-C-V pseudowords	0.89 (0.31)	0.75 (0.43)	10.61	0.001

Note: All tasks were scored as average proportion correct for this table.
Abbreviations: C-V-C, consonant-vowel-consonant structure; C-C-V, consonant-consonant-vowel structure; *M*, mean; *SD*, standard deviation.